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Wind Energy

Renewable Energy Sources Course Program

Understanding Wind Power Systems

- **Context :** ***Economic and environmental challenge***
- **Problematic :** *Integration of Renewable Energy*
- **Objective of course (4,5 hours) :**

Bringing **necessary knowledge** for understanding wind power systems

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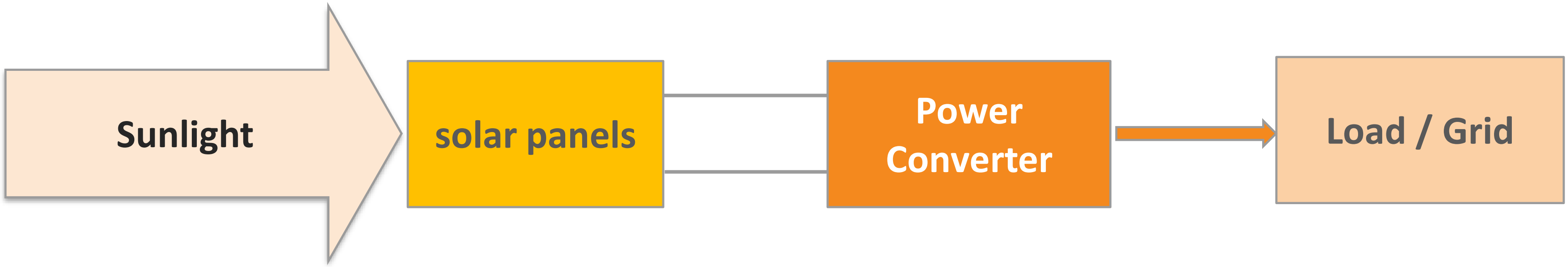
Overview - Chain of electricity generation



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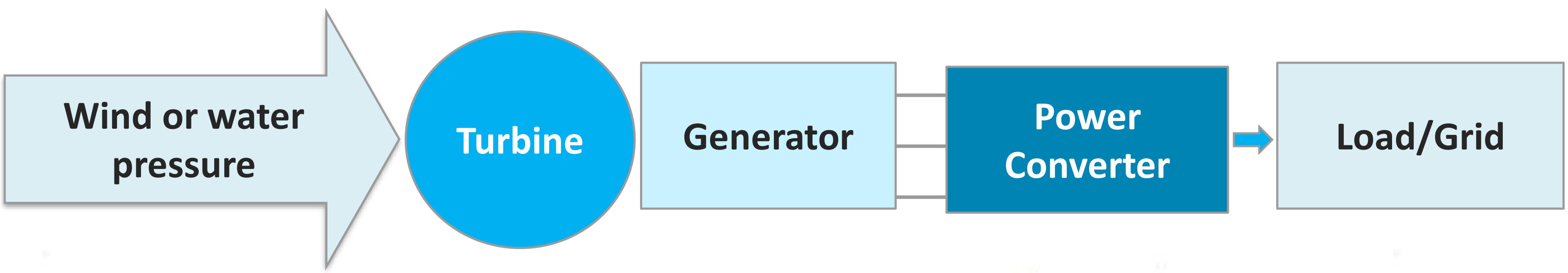


WIND Turbine / TIDAL

Origin of Wind

Wind – Atmospheric air in motion

<u>Energy source</u>

Solar radiation differentially absorbed by earth surface converted through convective processes due to temperature differences to air motion

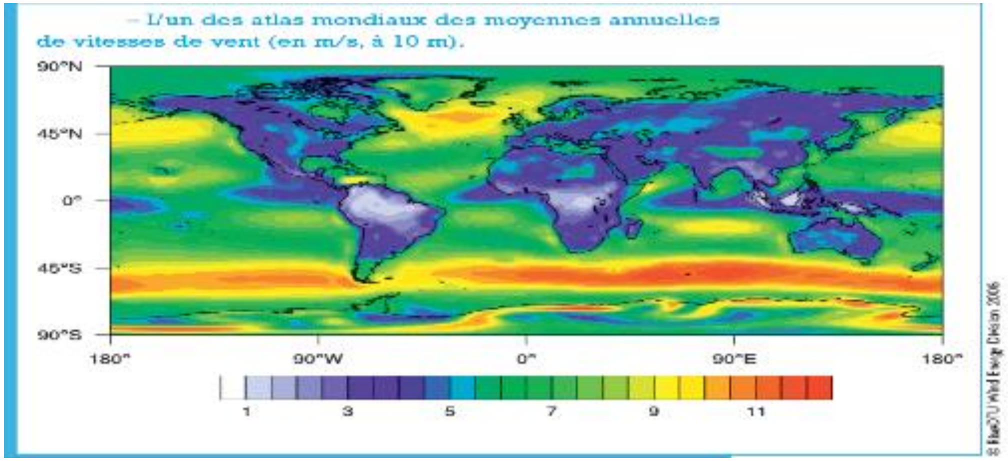
<u>Spatial Scales</u>

Planetary scale: global circulation

Synoptic scale: weather systems

Meso scale: local topography or thermally induced circulations

Micro scale: urban topography

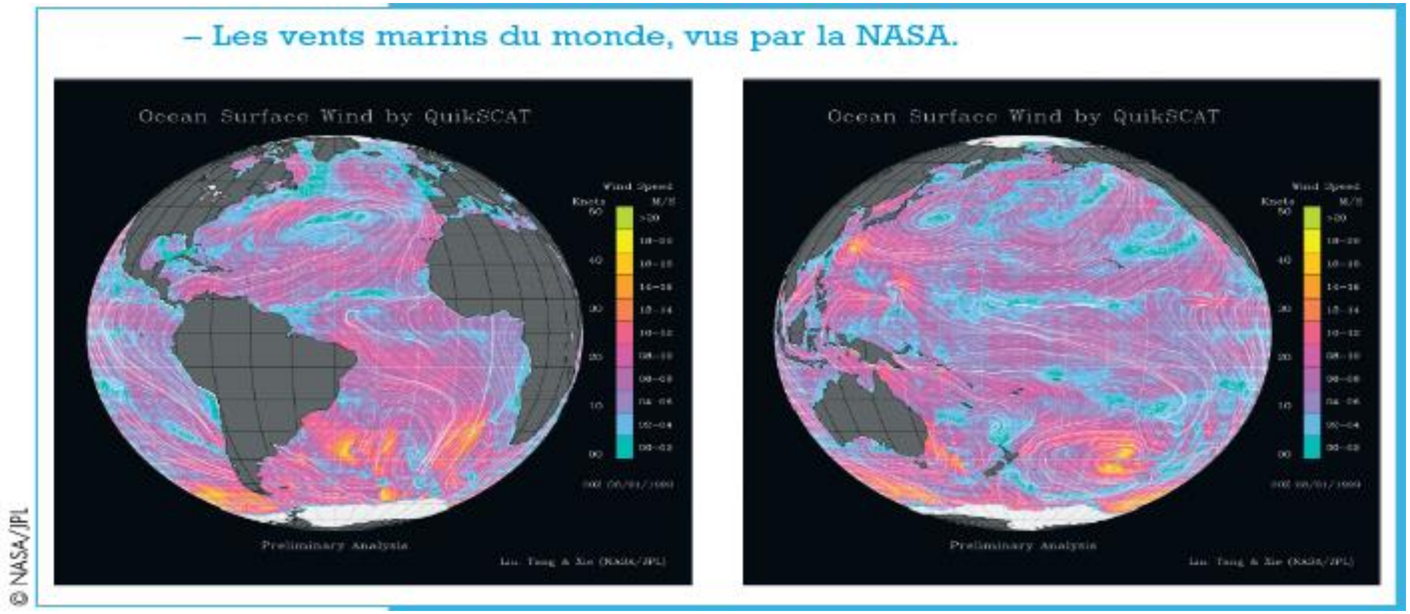


http://esri.github.io/wind-js/

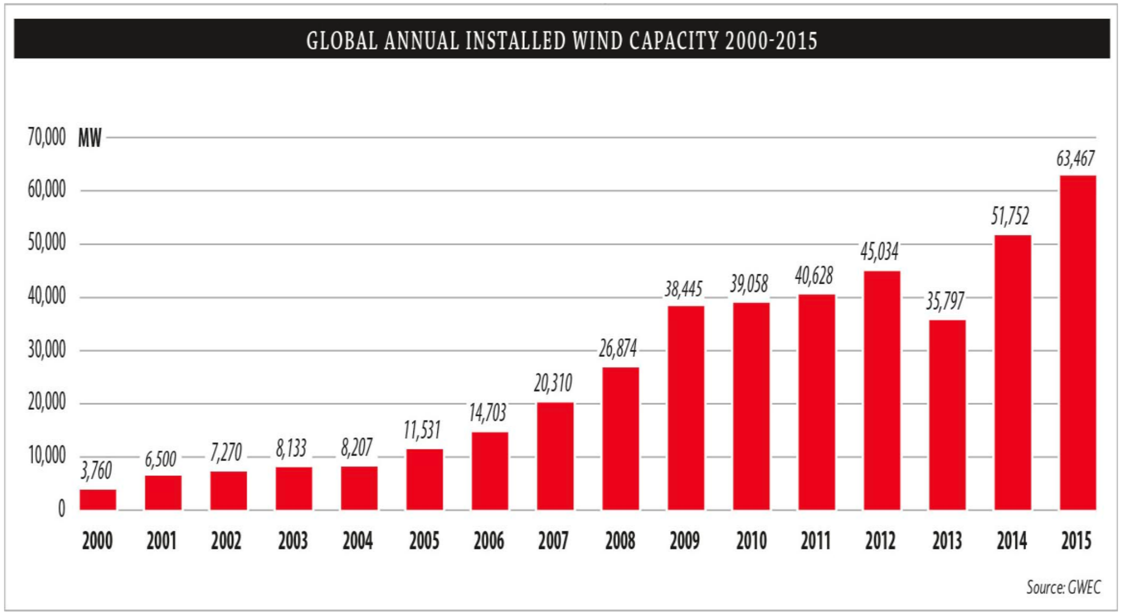
Origin of Wind

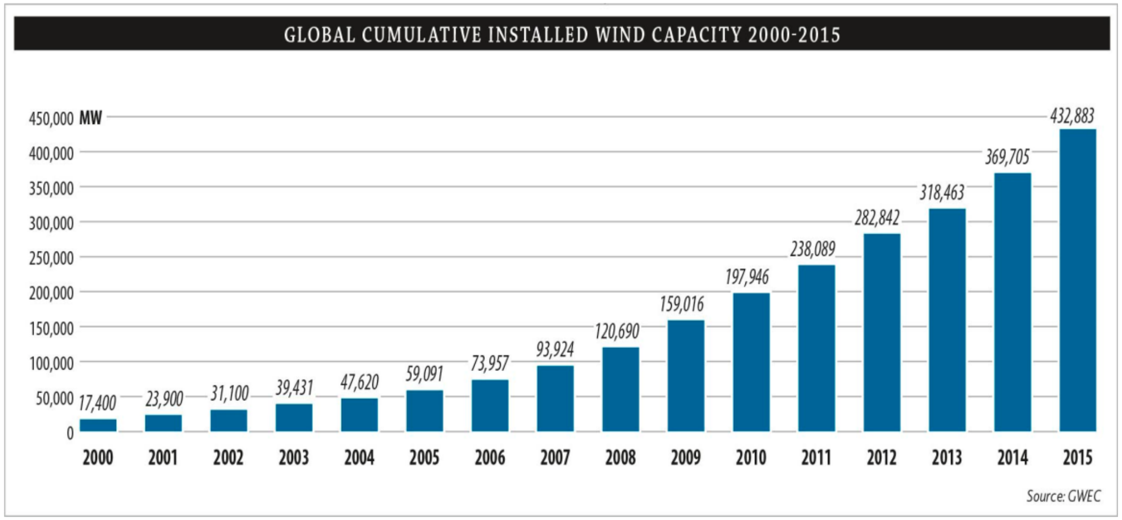
- An estimated 1% to 3% of energy from the Sun that hits the earth is converted into wind energy.

- The principle of wind is simple. The poles recieve less energy than the equater does from the sun. Also land heats up and cools down more quickly than the seas. This difference between the seas and the land causes a global atmospheric convection system.



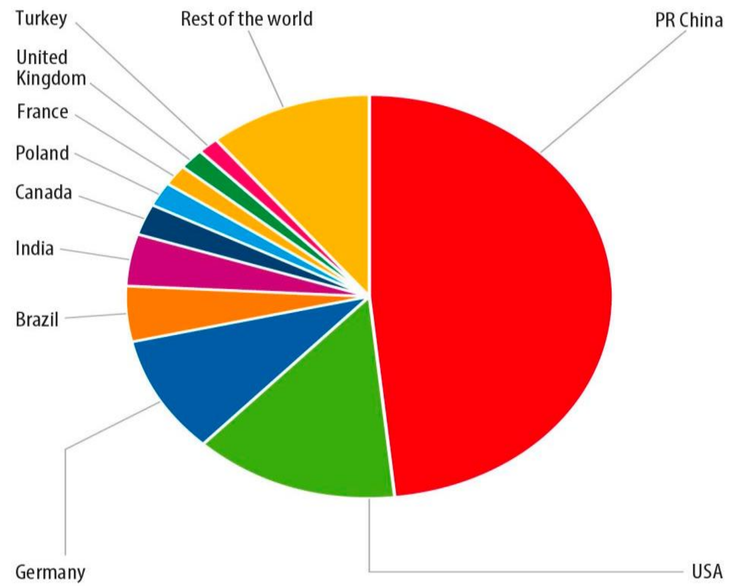
Growth in global wind installed power





Growth in global wind installed power

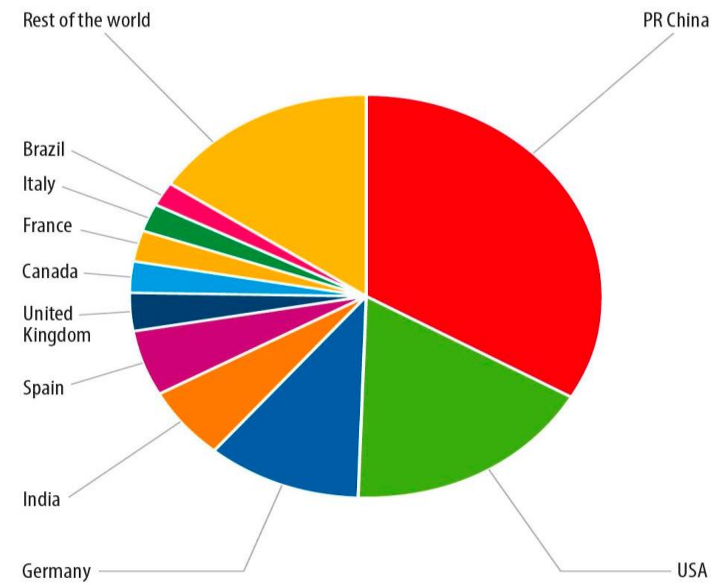
TOP 10 NEW INSTALLED CAPACITY JAN-DEC 2015



Country	MW	% Share
PR China	30,753	48.5
USA	8,598	13.5
Germany	6,013	9.5
Brazil	2,754	4.3
India	2,623	4.1
Canada	1,506	2.4
Poland	1,266	2.0
France	1,073	1.7
United Kingdom	975	1.5
Turkey	956	1.5
Rest of the world	6,950	11.0
Total TOP 10	**56,517**	**89**
World Total	**63,467**	**100**

Source: GWEC

TOP 10 CUMULATIVE CAPACITY DEC 2015



Country	MW	% Share
PR China	145,362	33.6
USA	74,471	17.2
Germany	44,947	10.4
India	25,088	5.8
Spain	23,025	5.3
United Kingdom	13,603	3.1
Canada	11,205	2.6
France	10,358	2.4
Italy	8,958	2.1
Brazil	8,715	2.0
Rest of the world	67,151	15.5
Total TOP 10	**365,731**	**84.5**
World Total	**432,883**	**100**

Source: GWEC

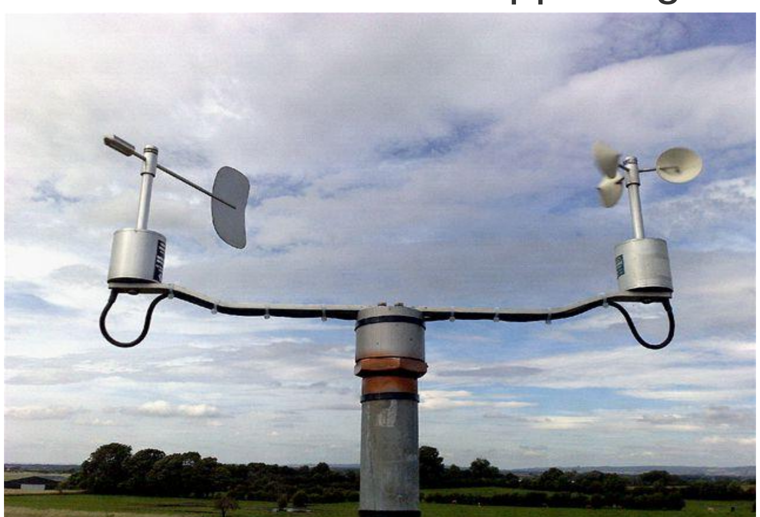
Wind speed measurement

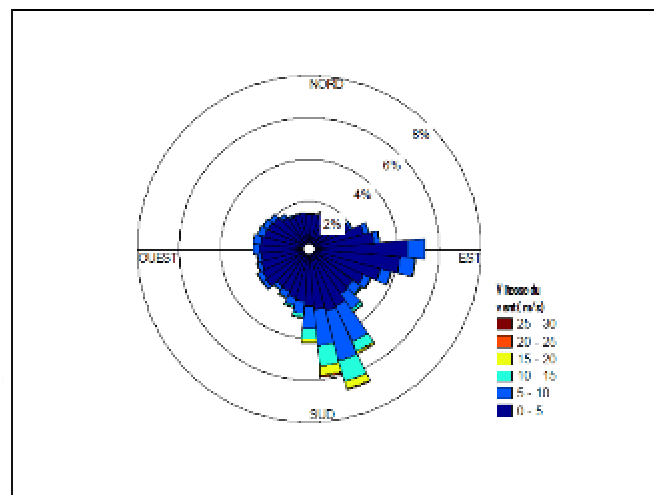
Cup anemometer

Wind speed is normally measured by a cup anemometer consisting of three or four cups, conical or hemispherical in shape, mounted symmetrically about a vertical spindle.

Measuring wind direction

Wind direction is measured by a vane consisting of a thin horizontal arm carrying a vertical flat plate at one end with its edge to the wind and at the other end a balance weight which also serves as a pointer. The arm is carried on a vertical spindle mounted on bearings which allow it to turn freely in the wind. The anemometer and wind vane are each attached to a horizontal supporting arm at the top of a 10 m mast.



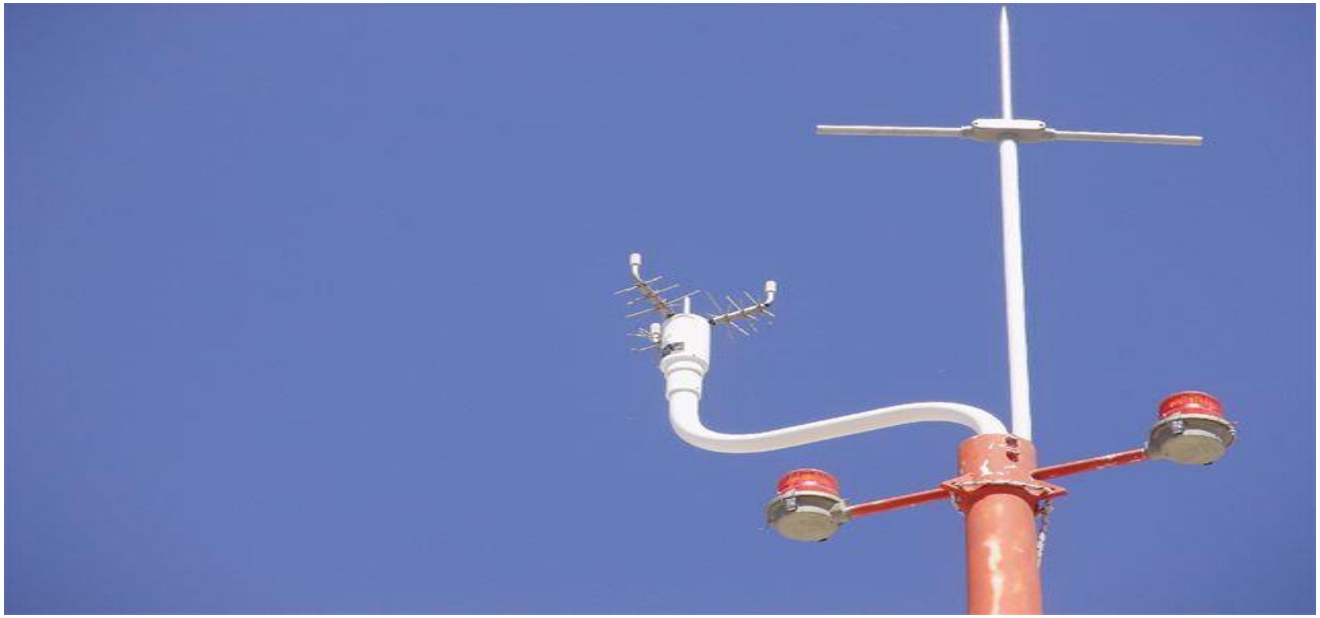


Wind speed measurement

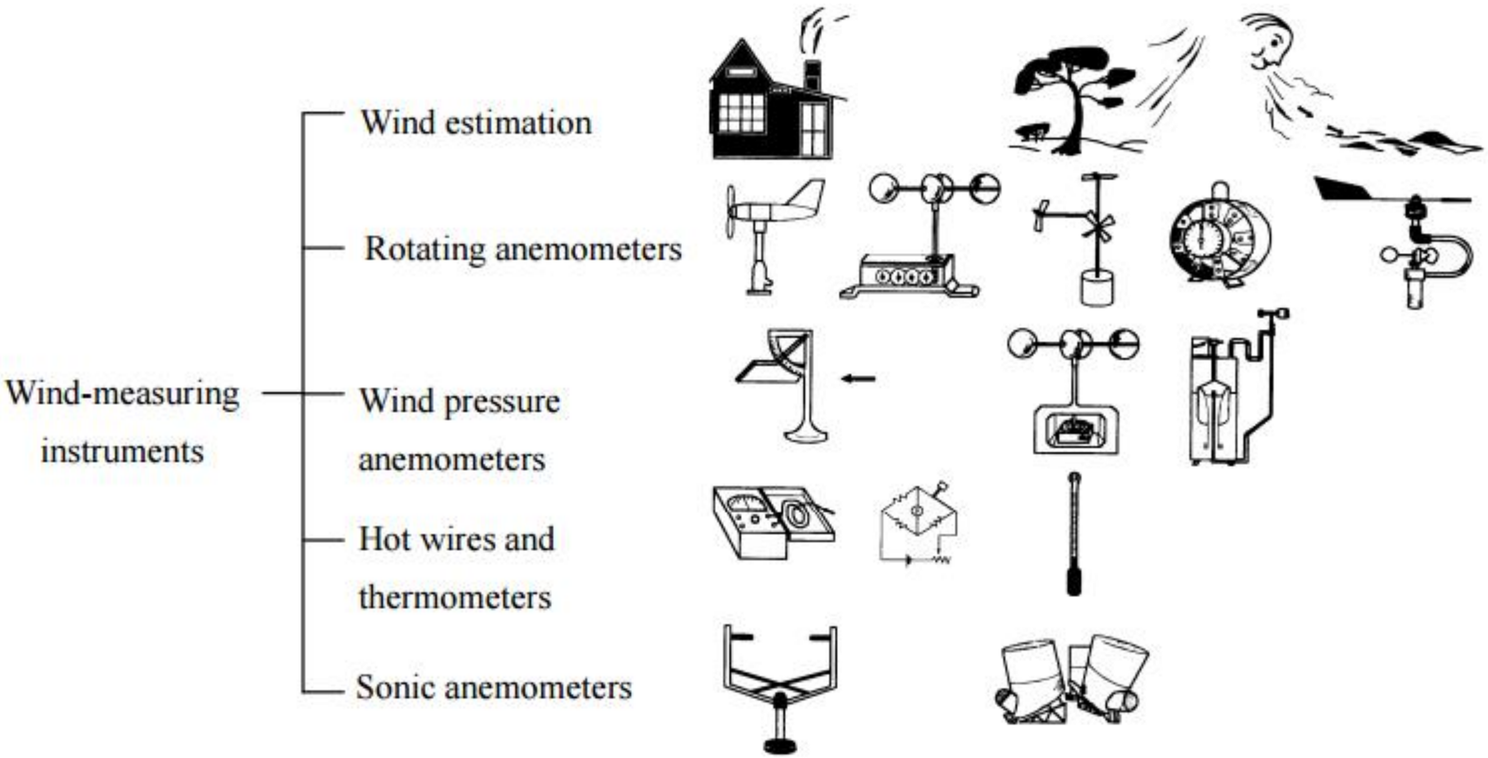
Wind speed measurement

Sonic anemometer

Where wind measurements are made in extreme weather conditions, such as on the top of mountains, a heated sonic anemometer is used (see above image) having no moving parts. The instrument measures the speed of acoustic signals transmitted between two transducers located at the end of thin arms. Measurements from two pairs of transducers can be combined to yield an estimate of wind speed and direction.
The distortion of the air flow by the structure supporting the transducers is a problem which can be minimized by applying corrections based on calibrations in a wind tunnel.



Wind speed measurement



Wind-measuring instruments

Wind Speed Frequency Distribution

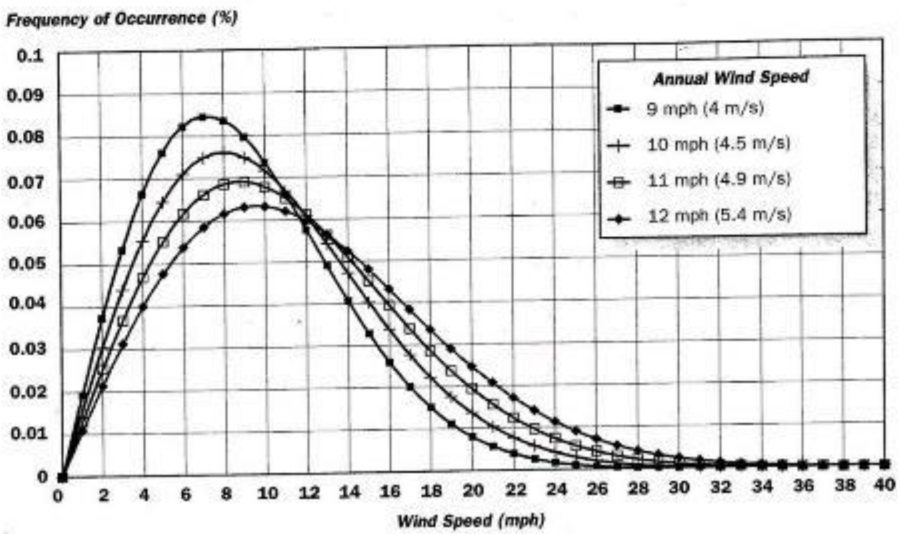


Chart plotting the frequency of different wind speeds at various annual average wind speeds for a Rayleigh distribution. The units are in percent of occurrence or the percent of time the wind will occur at that wind speed.

- Wind speeds occur at different values
- Total energy from a turbine depends heavily on the maximum speeds because Power increases with the cube of the speed

"The average of the cubes is greater than the cube of the average."

Wind Energy potential assessment

Energy output estimation for wind turbines has been dealt by a number of researchers and references. Some authors implement simple methods evaluating a perturbation from mean wind speed and variance. For example, to calculate the available wind power, Kainkwa suggests a formula :

$$Pa = \frac{1}{2}\rho[\bar{V}^3 + 3\bar{V}\sigma^2]$$

Where ρ is the air density, $\bar{V}$ represents mean wind speed and σ^2 the variance of wind speed.

As well, Paul Gipe introduced the “swept area‟s method”. It consists of determining the wind power and then estimating the potential production of energy Ea, simply knowing the area swept by the rotor A:

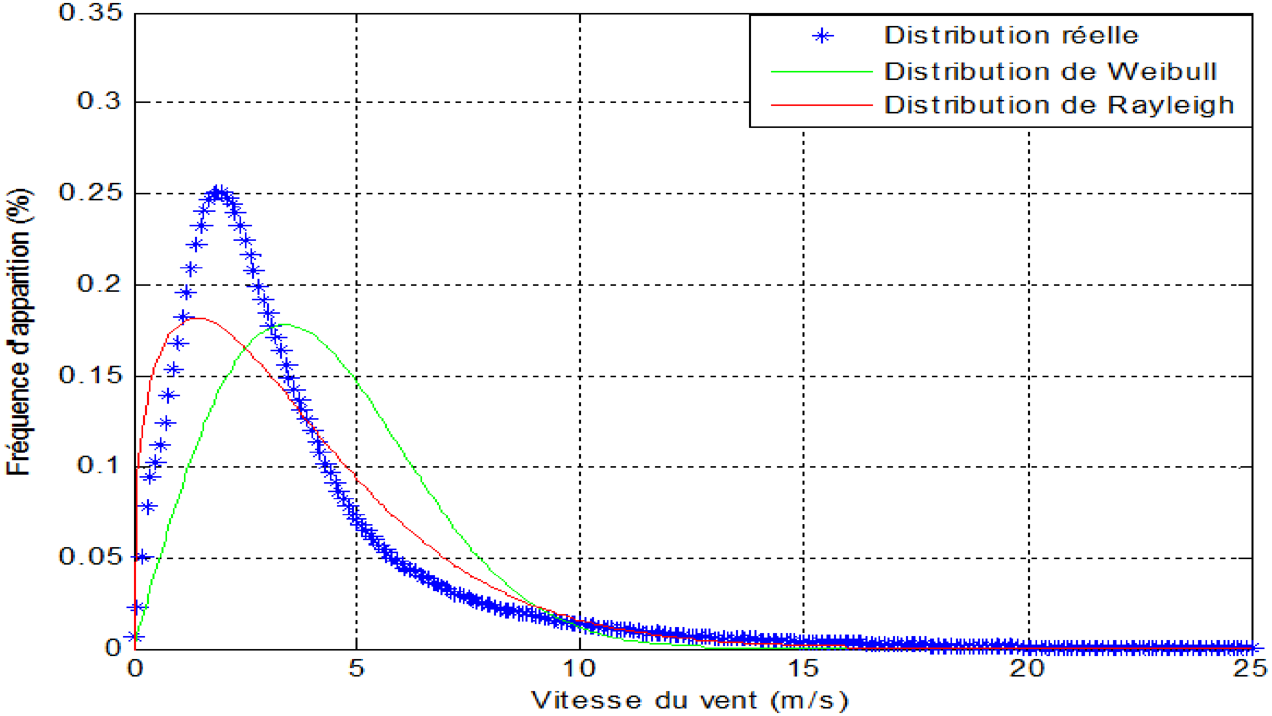
$$Ea = 8760\, h/year * 1kw/1000\, W * [\frac{1}{2}\rho A \bar{V}^3 F\eta]$$

With F is the Rayleigh distribution factor and η is the overall efficiency of the wind conversion system.

Wind Energy potential assessment

Energy estimation by Weibull distribution

Different wind speed distribution models are used to fit the wind speed distribution over a time period, such as the Weibull, the Rayleigh and the Lognormal.



Distribution de la vitesse du vent

Wind Energy potential assessment

Energy estimation by Weibull distribution

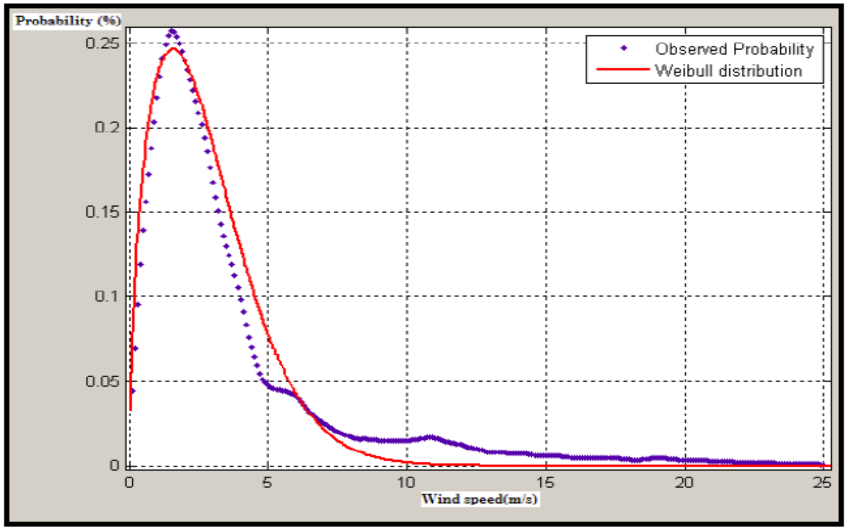
The Weibull probability density function has the following form:

$$f(V) = \frac{k}{c}\left(\frac{V}{c}\right)^{k-1} \exp\left[-\left(\frac{V}{c}\right)^{k}\right]$$

The corresponding cumulative distribution function is:

$$F(V) = 1 - \exp\left[-\left(\frac{V}{c}\right)^{k}\right]; (k > 0, V > 0, C > 0)$$

Where V is wind speed and c and k are two parameters, called the scale and shape parameters, respectively.



Probability plot and Weibull distribution curve fitting of wind data January 2007- National Technology Center-Colorado

Wind Energy potential assessment

Energy estimation by Weibull distribution

To determine the energy capture of the turbine over a time period T, we can just multiply the power Pe by f (V) * T so that the energy captured over a time period T (ignoring down time) will be:

$$E = T\int_{Vi}^{Vo} Pe(V) * f(V)dV$$

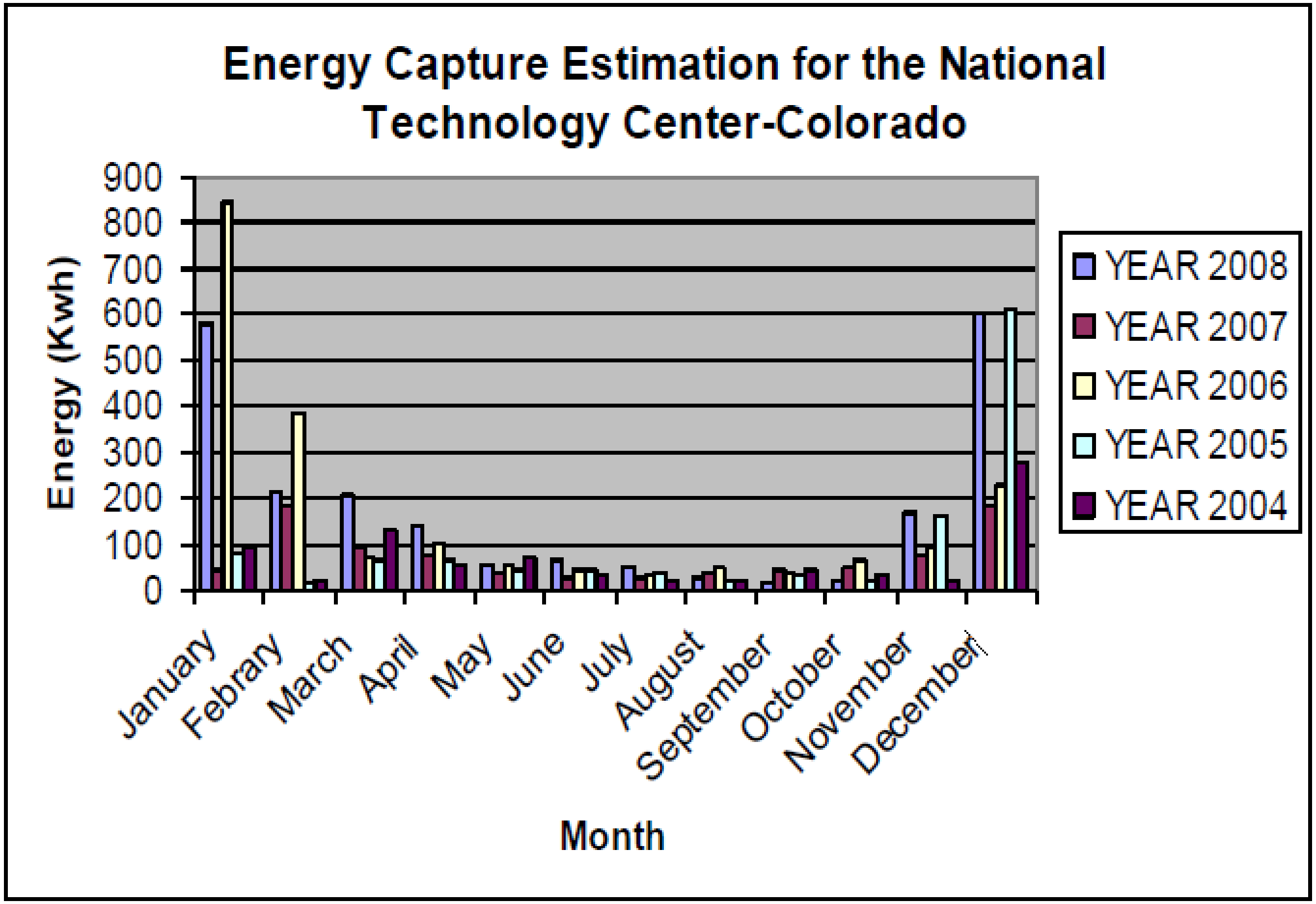
With Vi is the wind cut in speed (4m/s) and Vo is the cut out wind speed (25 m/s). Unfortunately, the integral does not have a closed mathematical form in general and so a numerical integration is required, such as the trapezoidal rule or Simpson"s rule.

Within one year time period and for 10 data wind points, the energy capture will be, using the trapezoidal rule,

$$E = 365 * 24 * \sum_{i-1}^{9} ((Pe(Vi+1)f(Vi+1) + Pe(Vi)f(Vi))(Vi+1-Vi))/2$$

Wind Energy potential assessment

Energy estimation by Weibull distribution

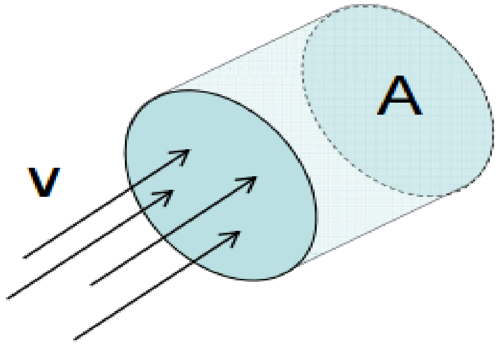


Energy Capture Estimation for the National Technology Center - Colorado using weibull distribution

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):
  - $dm/dt = \rho * A * v$
- Thus:
  - $P = ½ * \rho * A * v^3$

⇒

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

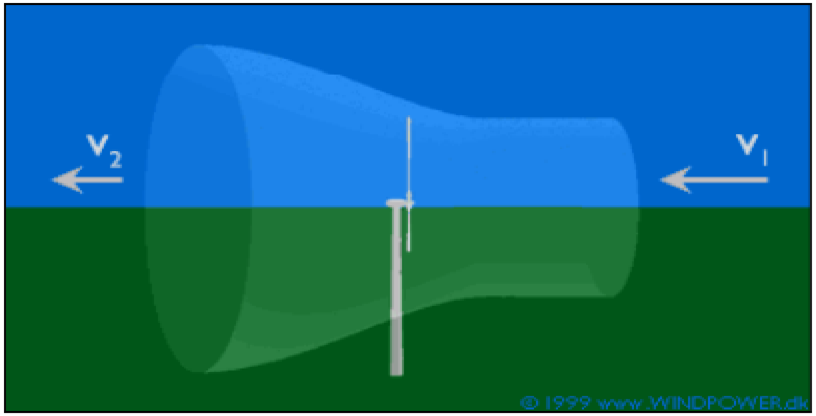
Efficiency in Extracting Wind Power

Betz Limit & Power Coefficient:

- Power Coefficient, **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

$$P_T = ½ * \rho * A * v^3 * Cp$$

- 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

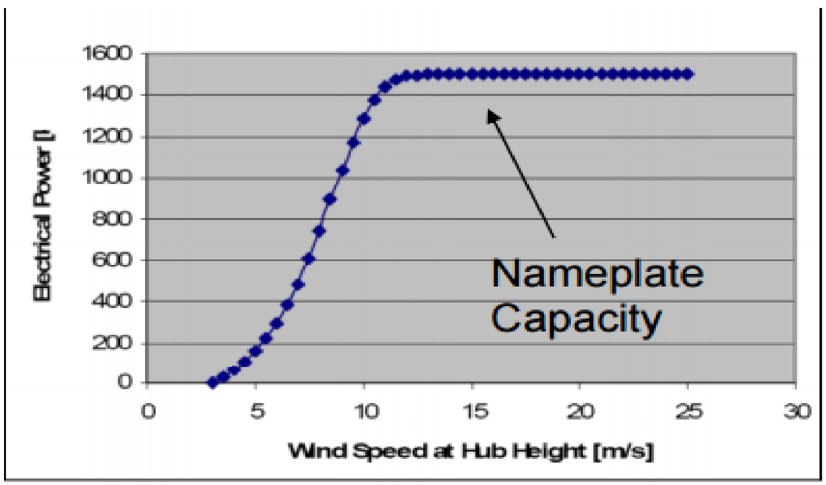
Capacity Factor (CF):

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

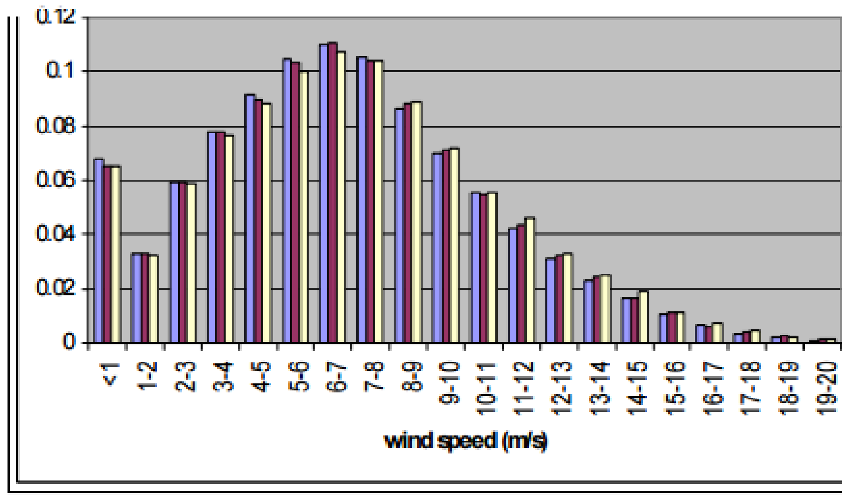
  Capacity Factor = Average Output / Peak Output ≈ 30%

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

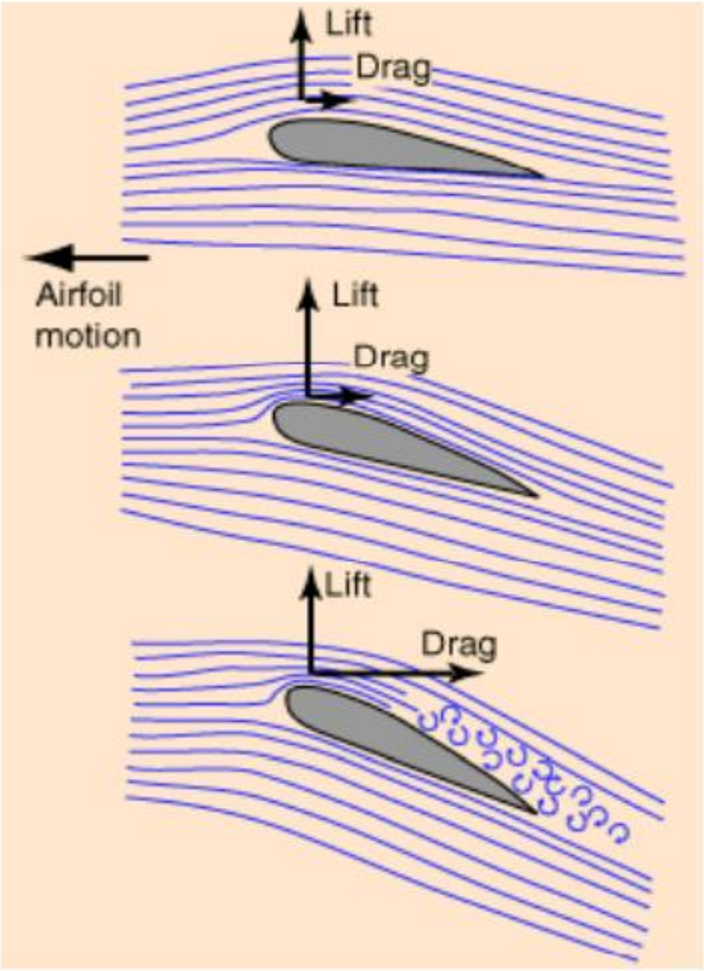
Power Curve of 1500 kW Turbine

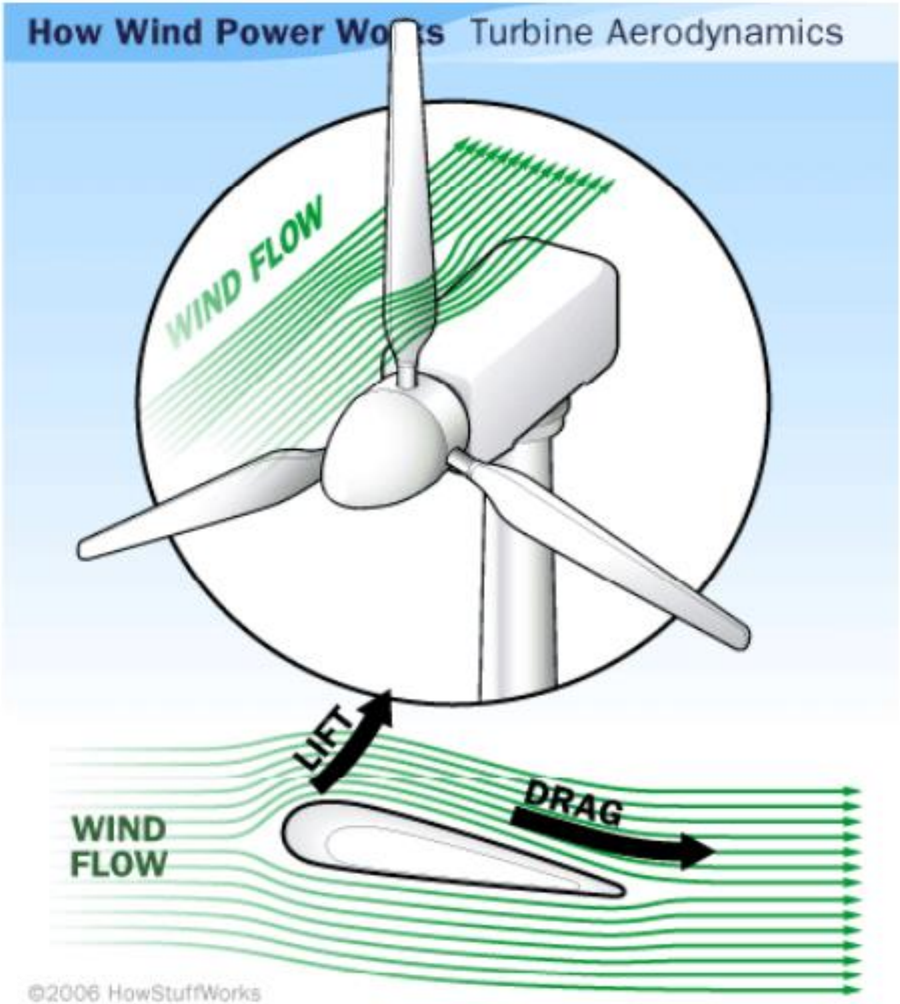


Wind Frequency Distribution



Lift and Drag Forces





Wind 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 Types

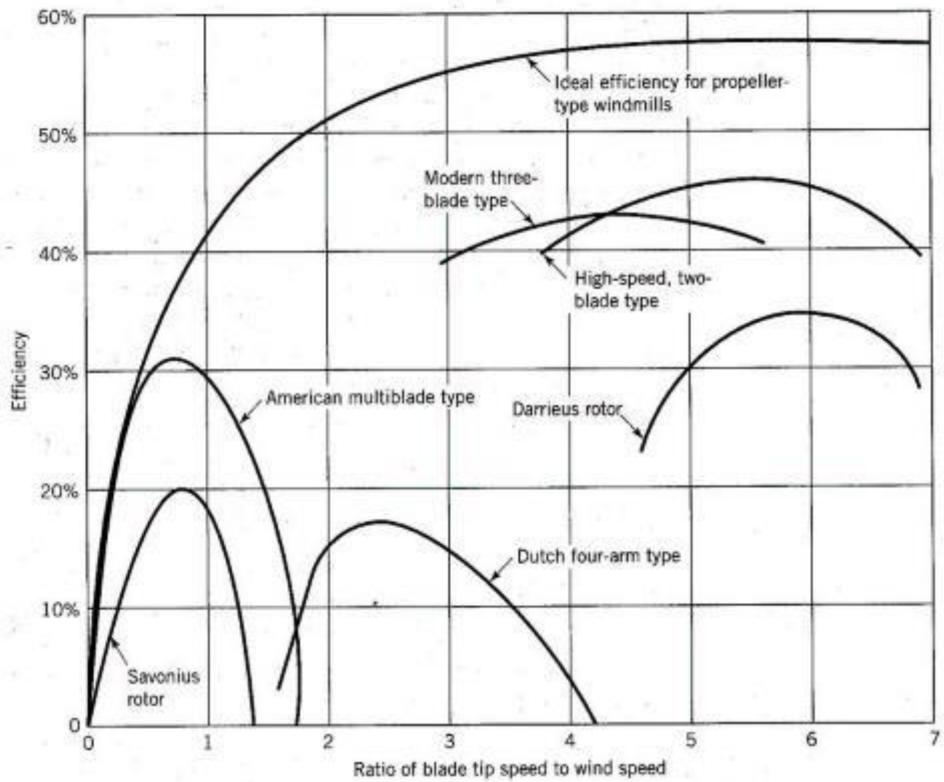
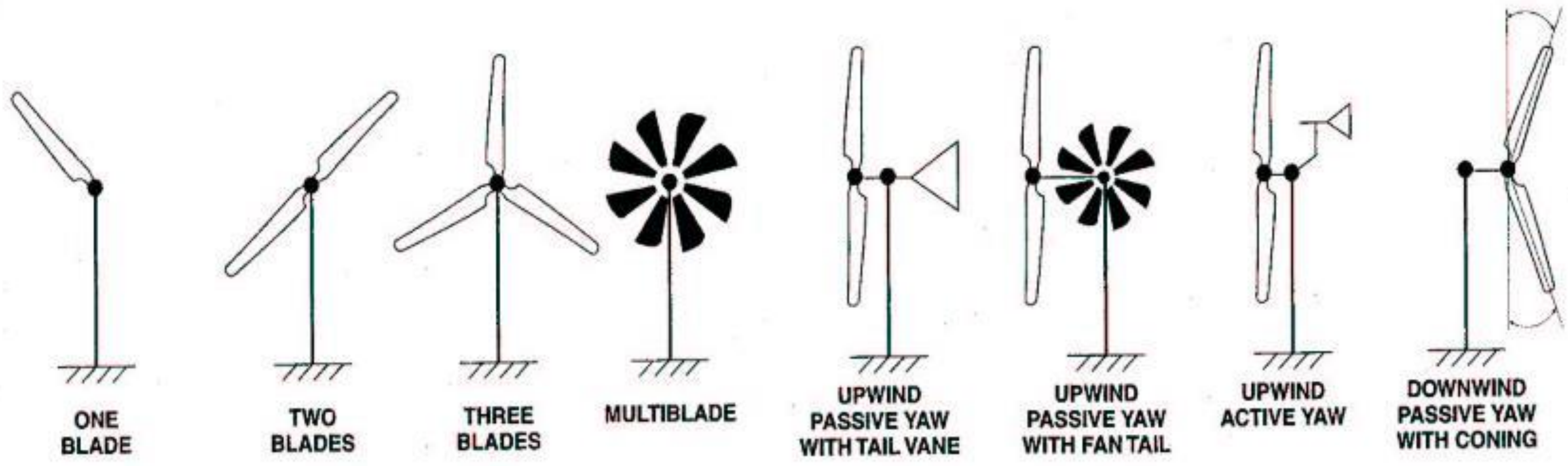


Figure 5.6 Typical efficiencies of several types of windmills plotted against their tip-speed ratio. The maximum efficiencies are seen to vary from about 16 to 46%. The ideal efficiency shown is a mathematical ideal, never to be achieved in practice. (Basic data from R. Wilson and P. Lissaman, *Applied Aerodynamics of Wind Power Machines*, Oregon State University.)

- The spinning of a windmill causes a “backwind” which is maximum at the blade tip.
- This affects the efficiency of the turbine.
- Thus, one factor in the design is the tip speed vs. wind speed ratio.

High technology large turbines can achieve up to 46% efficiency

Rotor Designs

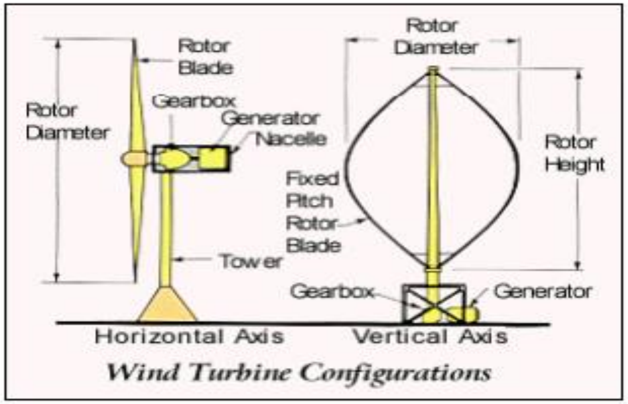


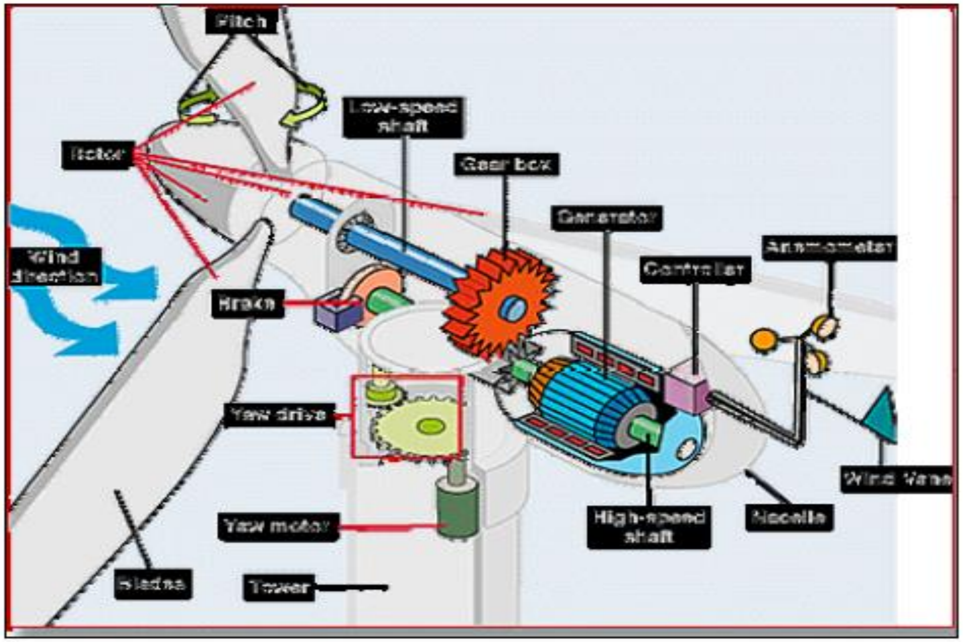
- Two blades are cheaper but do not last as long
- Three blades are more stable and last longer

- Options include:
  - Upwind vs downwind
  - Passive vs active yaw
- Common option chosen is to direct the rotor upwind of the tower with a tail vane

Wind Turbine Subsystems

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



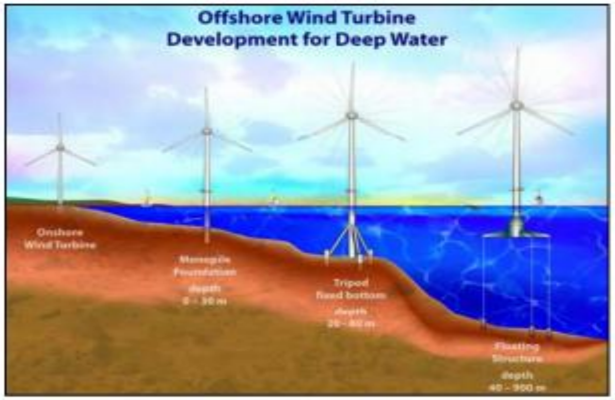


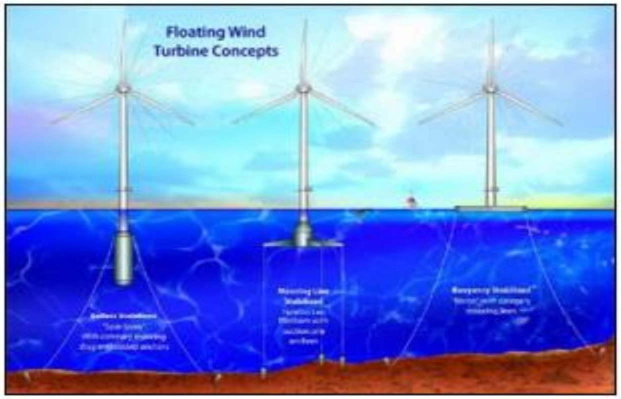
Source for Graphics: AWEA Wind Energy Basics, http://www.awea.org/faq/wwt_basics.html

Foundations and Tower

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

- Many different configurations proposed for offshore

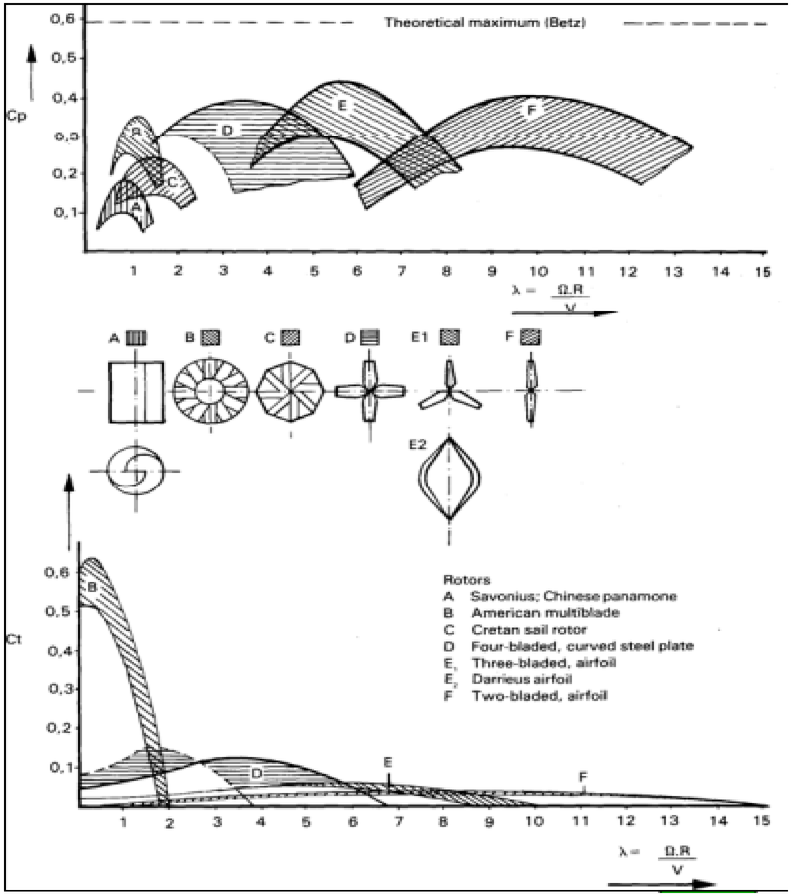




Images from National Renewable Energy Laboratory

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

Nacelle, Rotor & Hub

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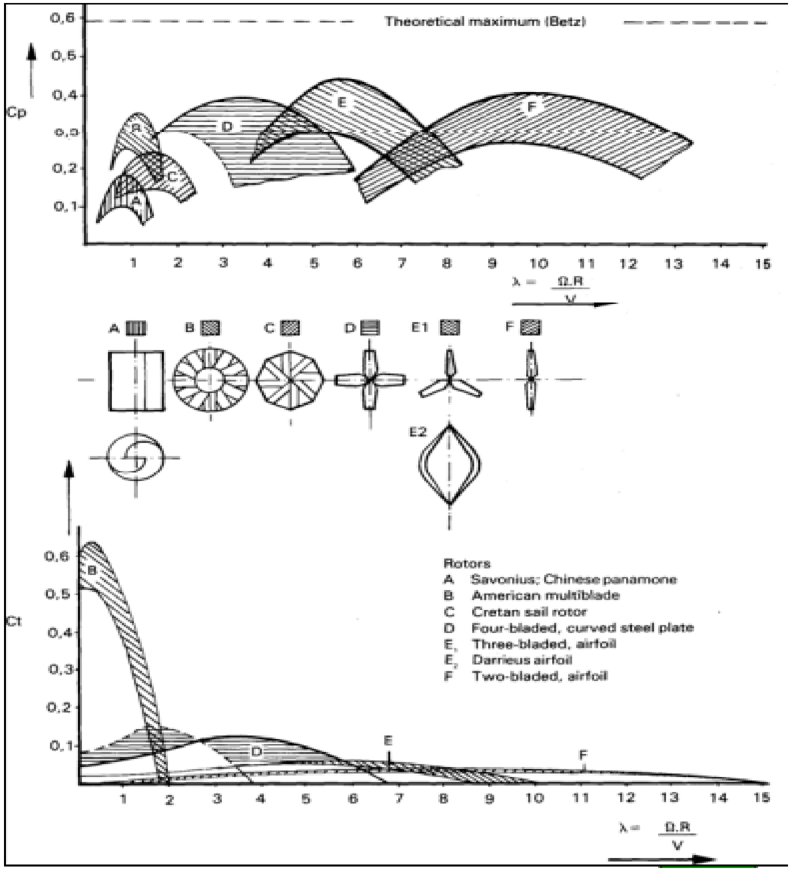
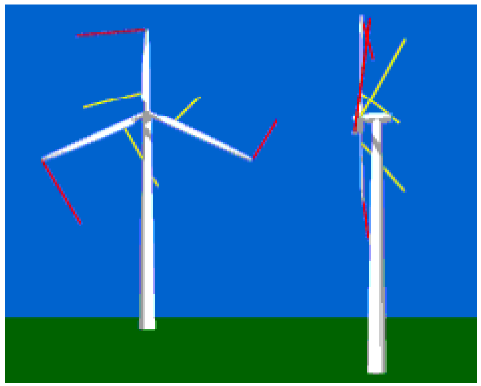


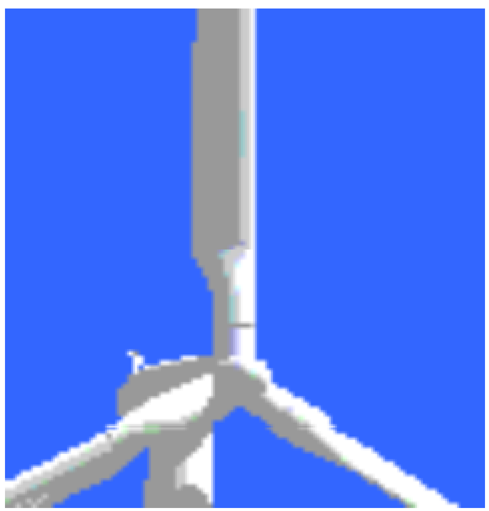
Graphic source Wind power: http://www.fao.org/docrep/010/ah810e/AH810E10.htm

Wind Turbine Blades

- Blade tip speed:



- Pitch control:

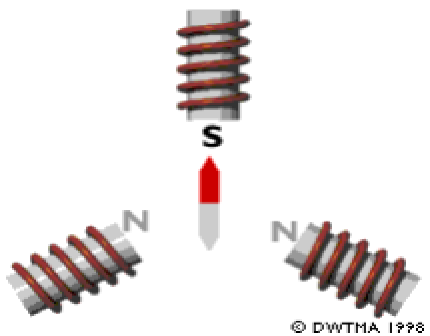


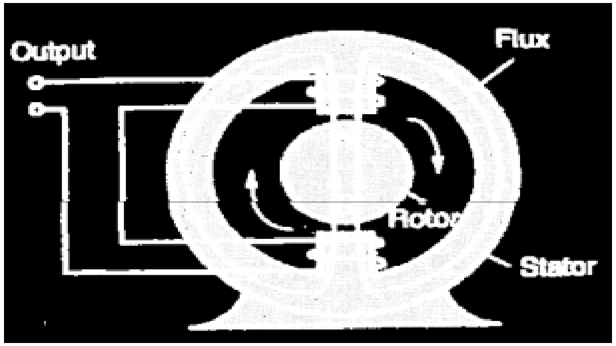
- 2-Blade Systems and Teetered Hubs:

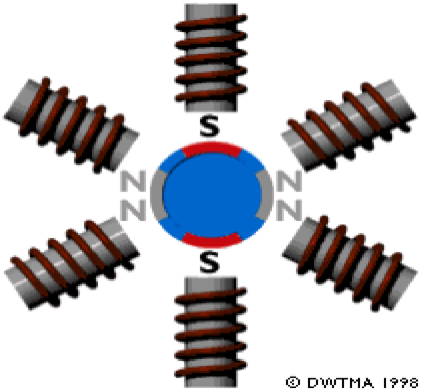
http://guidedtour.windpower.org/en/tour/wres/index.htm

Electrical Generator

- Generator:
  - Rotating magnetic field induces current





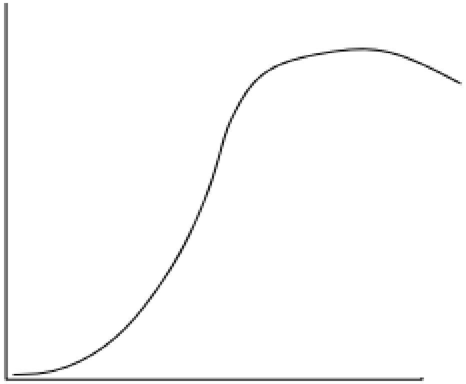


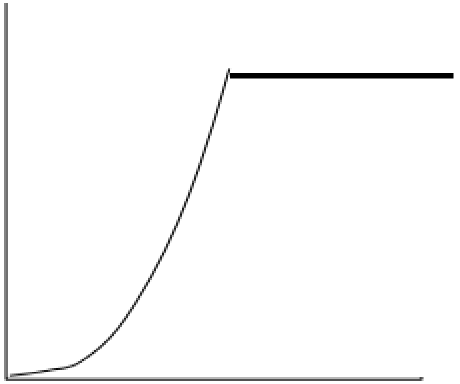
- Synchronous / Permanent Magnet Generator
  - Potential use without gearbox
  - Historically higher cost (use of rare-earth metals)
- Asynchronous / Induction Generator
  - Slip (operation above/below synchronous speed) possible
  - Reduces gearbox wear

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

Control Systems & Electronics

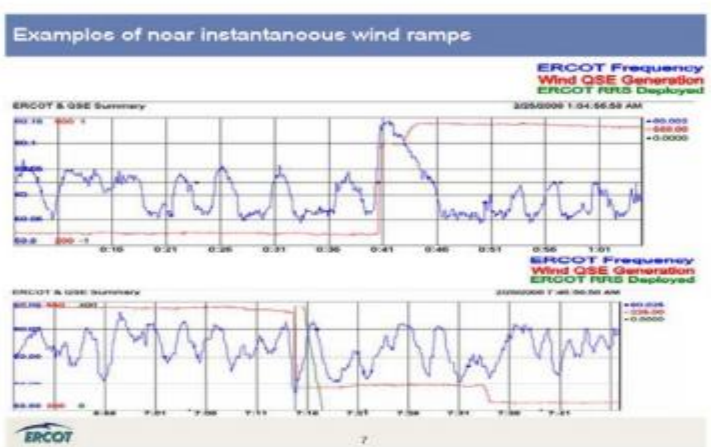
- Control methods
  - Drivetrain Speed
    - Fixed (direct grid connection) and Variable (power electronics for indirect grid connection)
  - Blade Regulation
    - Stall – blade position fixed, angle of attack increases with wind speed until stall occurs behind blade
    - Pitch – blade position changes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

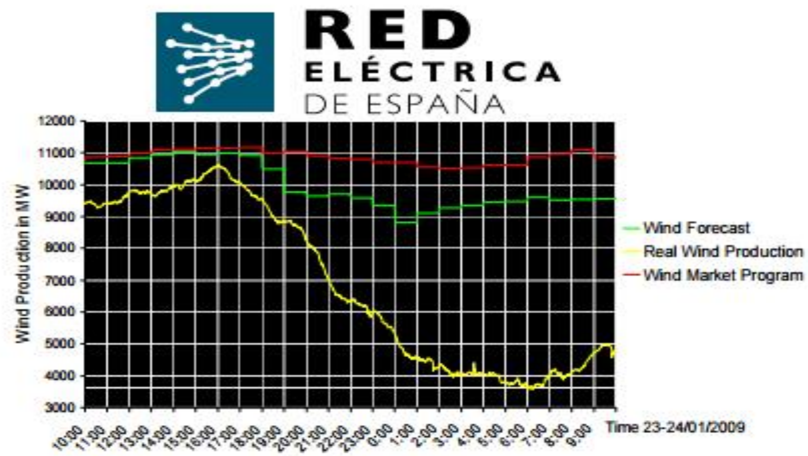




Wind Grid Integration

- 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)

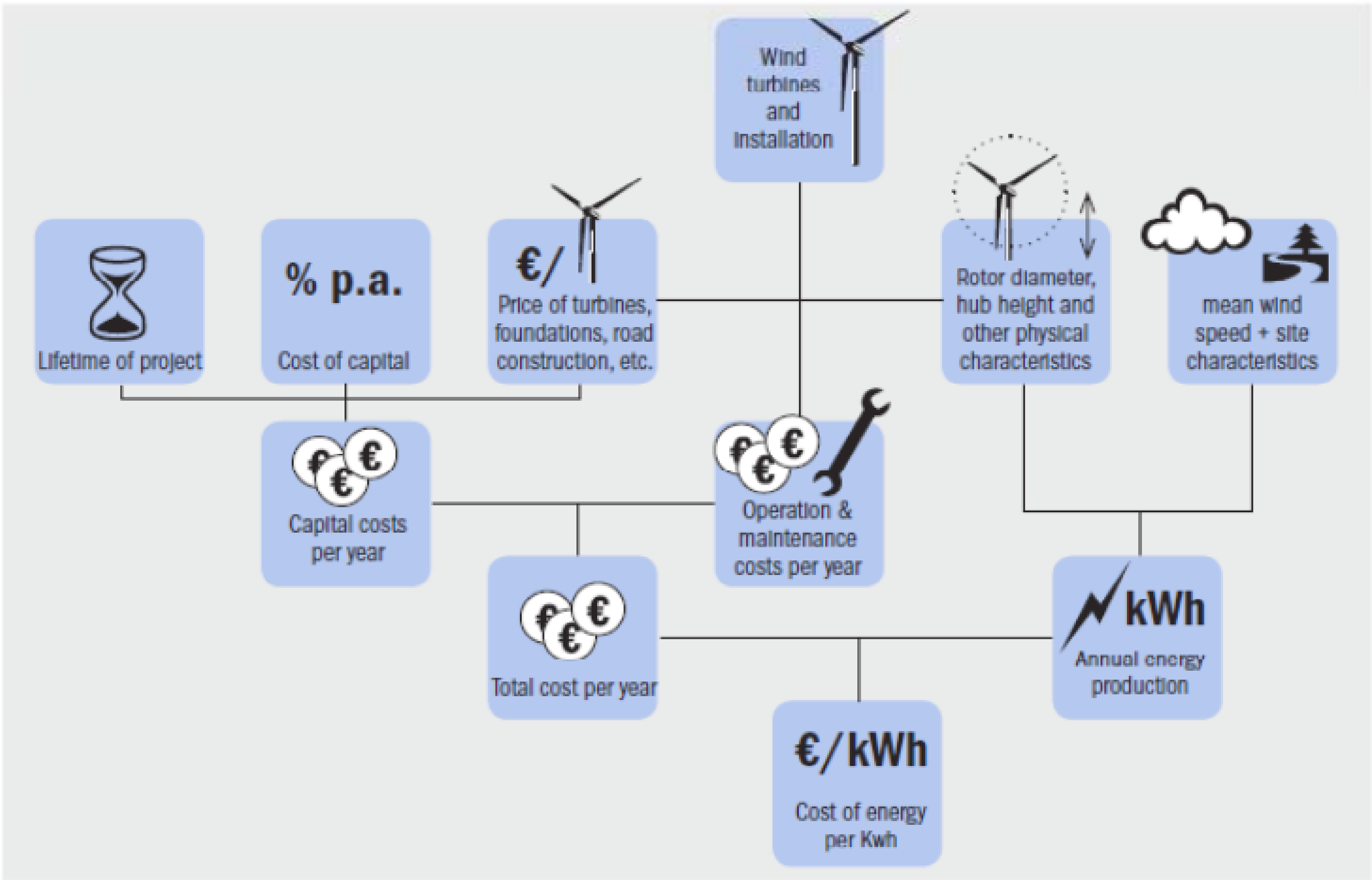




Left graphic courtesy of ERCOT

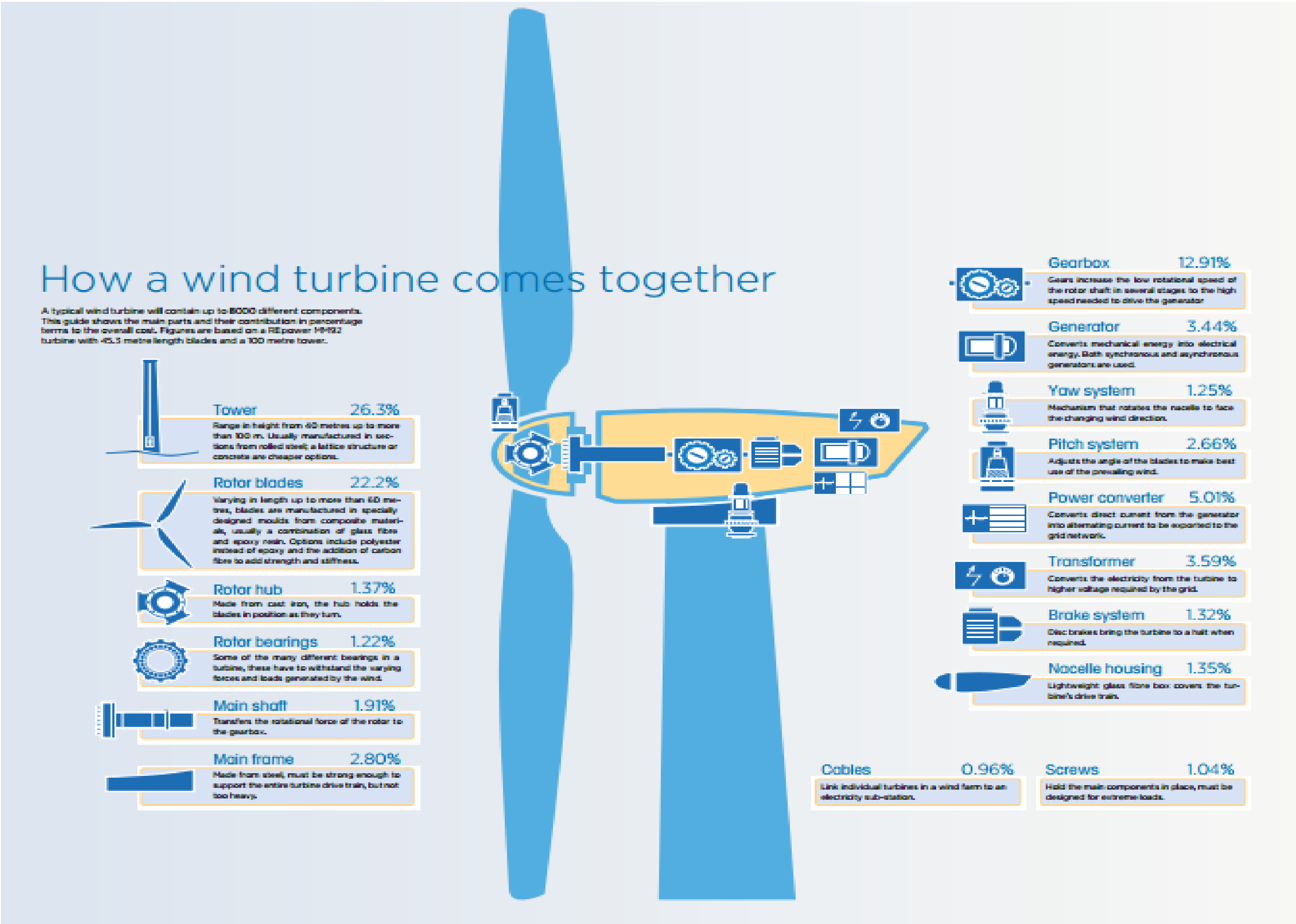
Right graphic courtesy of RED Electrica de Espana

Wind Energy Costs



Source: EWEA, 2009

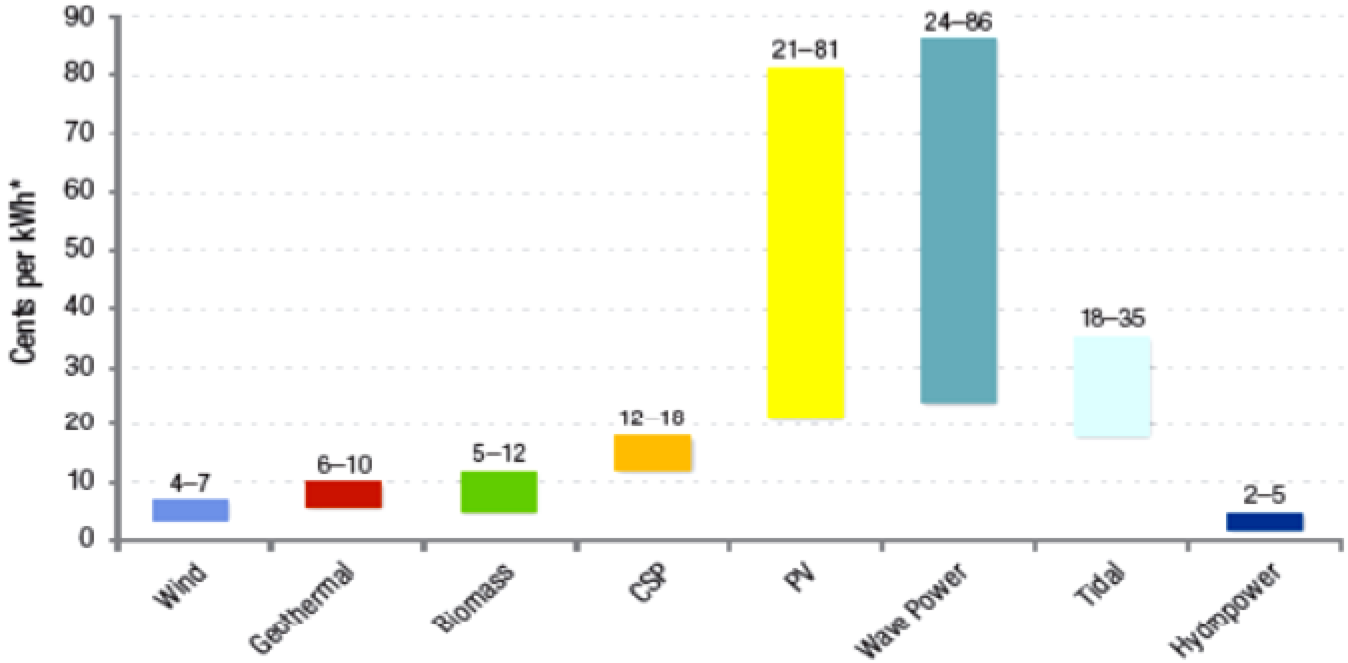
% Cost Share of 5 MW Turbine Components



WIND TURBINE COST BREAKDOWN (5 MW OFFSHORE WIND TURBINE)

Source: EWEA, 2007

Costs -- Levelized Comparison

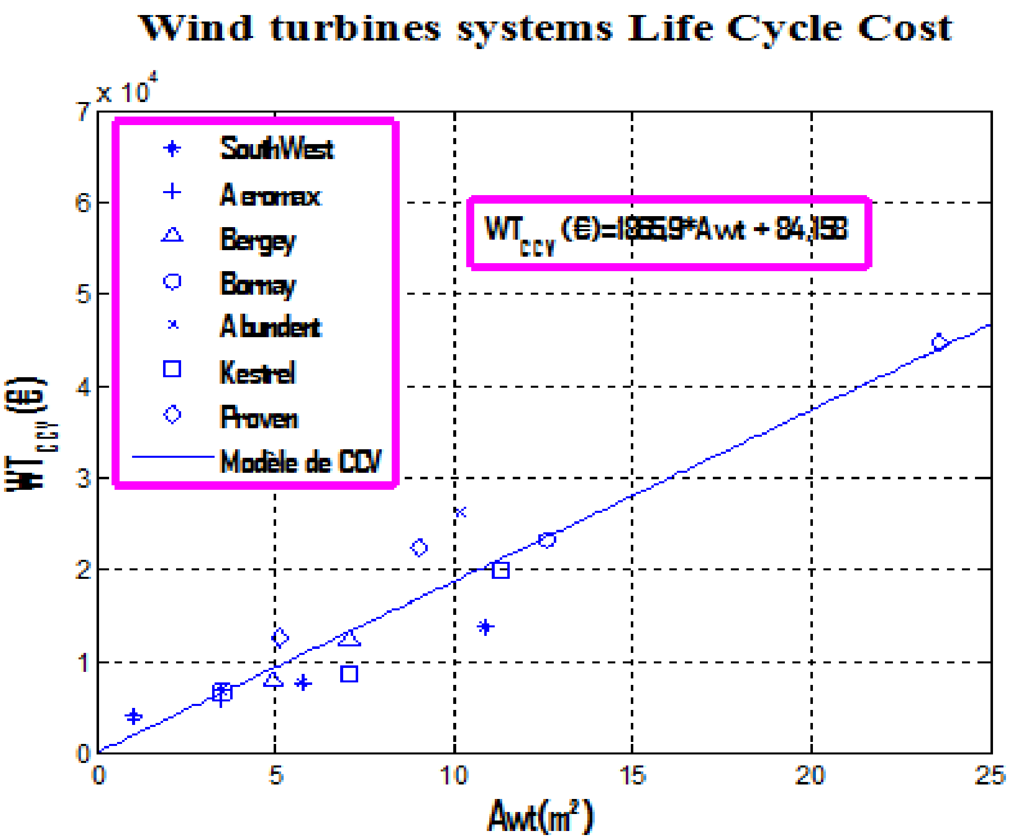


* Average cost will vary according to financing used and the quality of the renewable energy resource available.

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

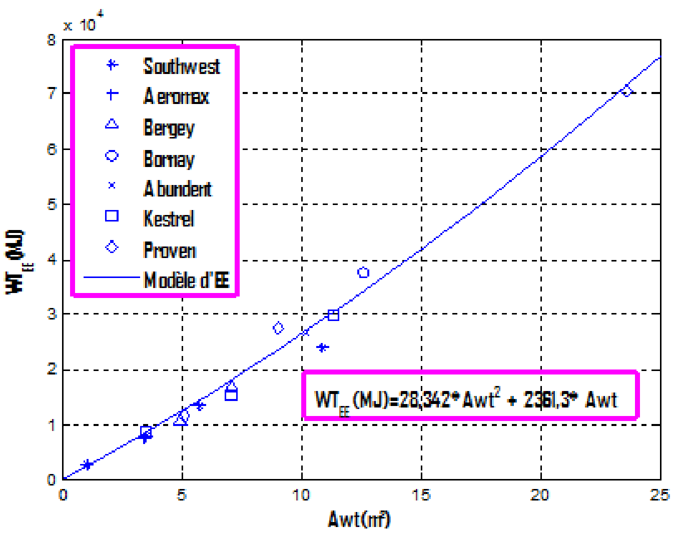
Life Cycle Cost of Small wind turbines



Batteries Life cycle Cost

Embodied energy of Small wind turbines

Wind turbines systems Embodied Energy assessment



Product	Swept area (m²)	Rated power of the turbine (W) (used to evaluate the energy embodied in the converter)	Wind Turbine Weight (kg)	Global embodied energy (MJ)	Global embodied energy (MJ)/m²
SouthWest (Air X)	1.020	400 (at 12.5 m/s)	5.850	2663.21	2610.99
SouthWest (Whisper 100)	3.460	900 (at 12.5 m/s)	21.000	7846.49	2267.77
SouthWest (Whisper 200)	5.725	1000 (at 11.6 m/s)	70.000	13364.67	2334.44
Southwest (Skystream 3,7)	10.870	2400 (at 13 m/s)	77.000	24022.89	2210.02
Aeromax Engineering (Lacota S, SC)	3.430	900 (at 13m/s)	16.000	7565.54	2205.70
Bergey (BWC 1500)	7.070	1500 (at 12.5 m/s)	76.000	16718.42	2364.70
Bergey (BWC XL,1))	4.910	1000 (at 11 m/s)	34.000	10584.32	2155.67
Bornay (Inclin 6000)	12.570	6000 (at 12 m/s)	107.000	37431.12	2977.81
Abundent Renewable Energy (ARE110)	10.180	2500 (at 11 m/s)	143.000	26630.14	2615.93
Kestrel Wind (800)	3.460	800 (at 12.5 m/s)	45.000	8740.68	2526.21
Kestrel Wind (1000)	7.070	1000 (at 11m/s)	75.000	15308.68	2165.30
Kestrel Wind (3000)	11.340	3000 (at 11m/s)	150.000	29798.53	2627.74
Proven WT 0,6	5.100	600 (at 12m/s)	70.000	11485.33	2252.02
Proven WT 2,5	9.000	2500 (at 12m/s)	190.000	27422.06	3046.89
Proven WT 6	23.600	6000 (at 12m/s)	500.000	70480.75	2986.47

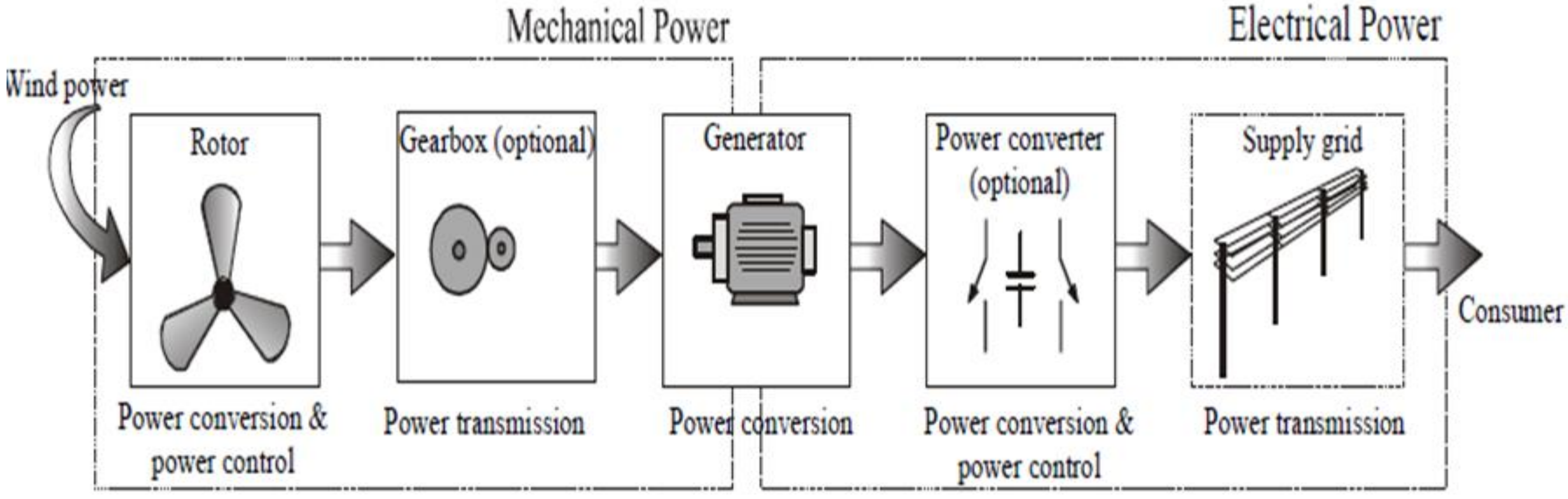
Different small wind turbines embodied energy


What's inside a wind turbine?

Wind power conversion

■ The function of a wind turbine is to convert the linear motion of the wind into rotational energy that can be used to drive a generator.

■ Wind turbines capture the power from the wind by means of aerodynamically designed blades and convert it into rotating mechanical power. At present, the most popular wind turbine is the Horizontal Axis Wind Turbine (HAWTs) where the number of blades is typically three.



Conversion from wind power to electrical power in a wind turbine

Wind power conversion

- The aerodynamic power, *P*, of a wind turbine is given by:

$$P = \frac{1}{2}\rho\pi R^2 v^3 C_p$$

where ρ is the air density, *R* is the turbine radius, *v* is the wind speed and *Cp* is the turbine power coefficient which represents the power conversion efficiency of a wind turbine. *Cp* is a function of the tip-speed ratio (λ), as well as the blade pitch angle (β) in a pitch controlled wind turbine. λ is defined as the ratio of the tip speed of the turbine blades to wind speed, and given by:

$$\lambda = \frac{R \cdot \Omega}{v}$$

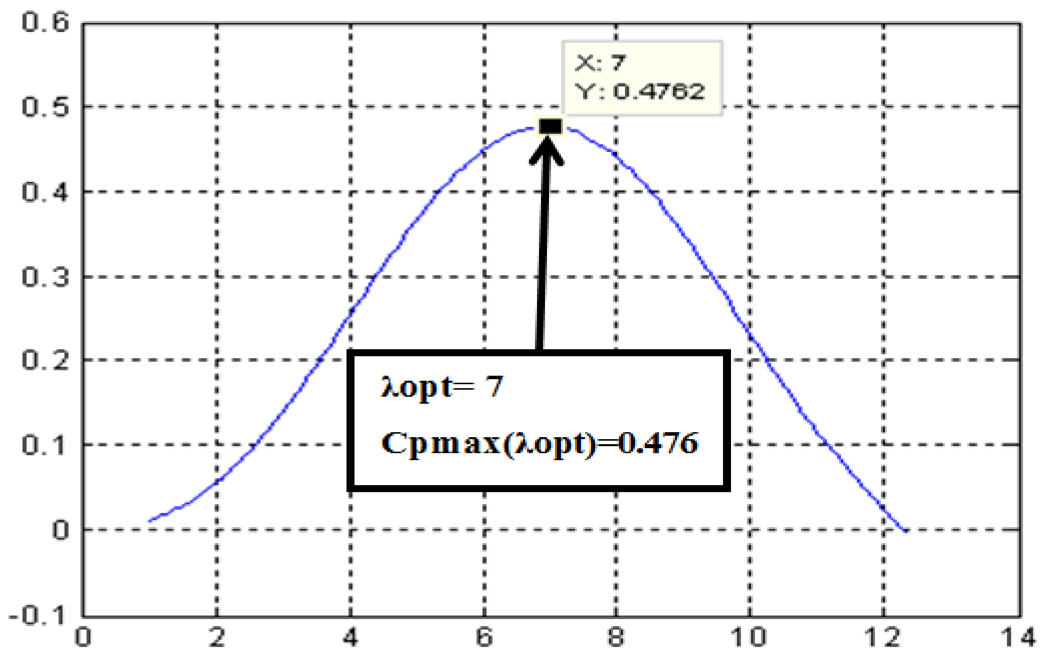
where Ω is the rotational speed of the wind turbine.

- The Betz limit, *CP*,max (theoretical) =16/27, is the maximum theoretically possible rotor power coefficient. In practice three effects lead to a decrease in the maximum achievable power coefficient :
  - Rotation of the wake behind the rotor
  - Finite number of blades and associated tip losses
  - Non-zero aerodynamic drag

* In fluid dynamics, the **drag coefficient** (commonly denoted as: c_d, c_x or c_w) is a dimensionless quantity that is used to quantify the drag or resistance of an object in a fluid environment such as air or water.

Wind power conversion

- A typical *Cp*-λ curve for a fixed pitch angle β is shown in Figure. It can be seen that there is a practical maximum power coefficient, *Cp*,max. Normally, a variable speed wind turbine follows the *Cp*,max to capture the maximum power up to the rated speed by varying the rotor speed to keep the system at the optimum tip-speed ratio, λopt.



Characteristic Cp (λ) of a wind turbine for a fixed angle β

Fixed speed wind power conversion system

- In a fixed speed wind power conversion system, the power may be limited aerodynamically either by stall, active stall or by pitch control. Normally induction generators are used in fixed speed systems, which are almost independent of torque variation and operate at a fixed speed (slip variation of 1-2%).

- All three systems are using a soft-starter in order to reduce the inrush current and there by limit flicker problems on the grid. They also need a reactive power compensator to reduce (almost eliminate) the reactive power demand from the turbine generators to the grid. It is usually done by continuously switching capacitor banks following the production variation (5-25 steps).

- Those solutions are attractive due to cost and reliability but they are not able (within a few ms) to control the active power very fast. The generators have typically a pole-shift possibility in order to maximize the energy capture.

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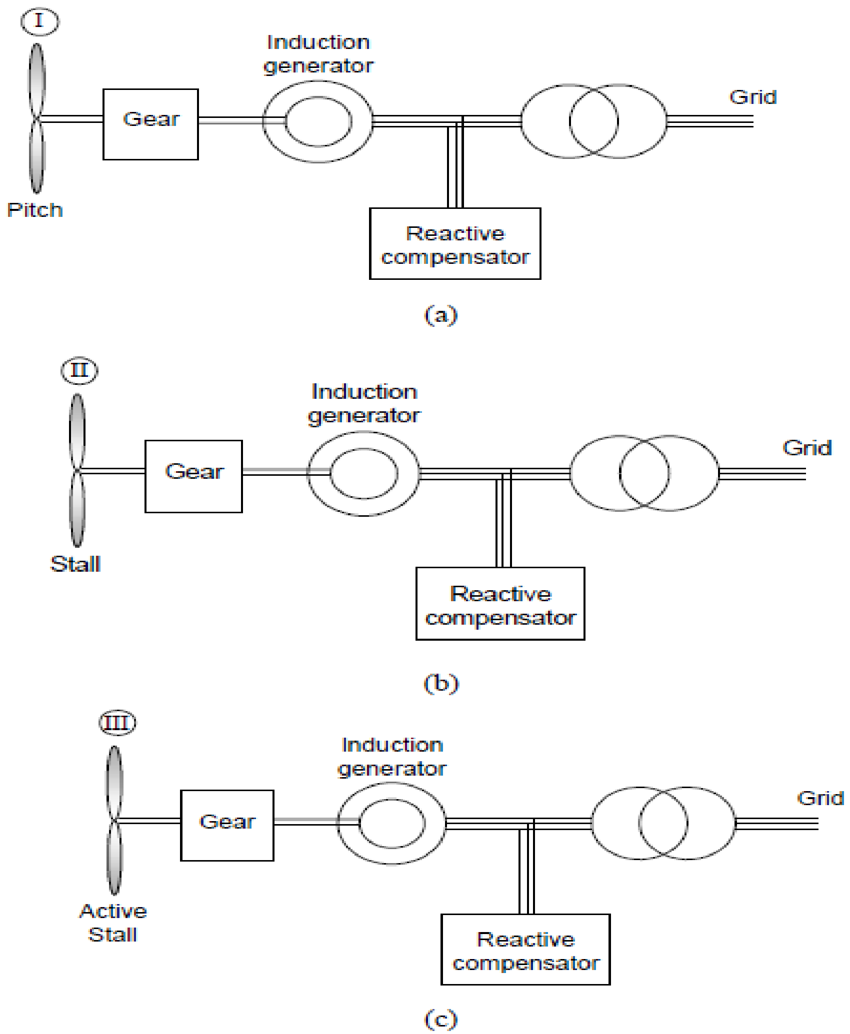
Fixed speed wind power conversion system



Wind turbine systems without power converter but with aerodynamic power control.

a) Pitch controlled (System I)

b) Stall controlled (System II)

c) Active stall controlled (System III)

There are two basic approaches used to control a wind turbine in high wind speeds: pitch-control and stall-control. In pitch-controlled turbines, an anemometer mounted atop the nacelle constantly checks the wind speed and sends signals to a pitch actuator, adjusting the angle of the blades to capture the energy from the wind most efficiently. On a stall-regulated wind turbine, the blades are locked in place and do not adjust during operation. Instead the blades are designed and shaped to increasingly “stall” the blade’s angle of attack with the wind to both maximize power output and protect the turbine from excessive wind speeds.

Fixed speed wind power conversion system

- **Benefits**

✓ Simple and well known system

✓ Economic

- **Disadvantages**

❖ Energy losses due to the multiplier

❖ Significant vibrations

❖ Significant noise

❖ Faster wear

❖ Oil maintenance of the multiplier (risk of leaks)

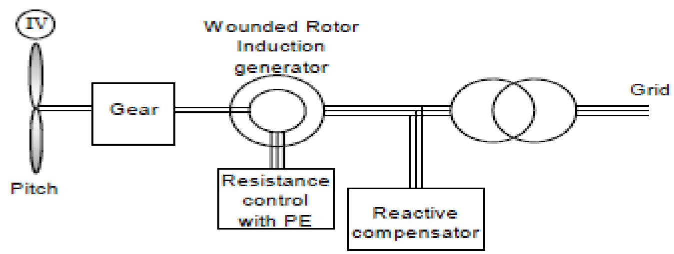
❖ Higher fire risk

❖ The electricity produced is of lower quality

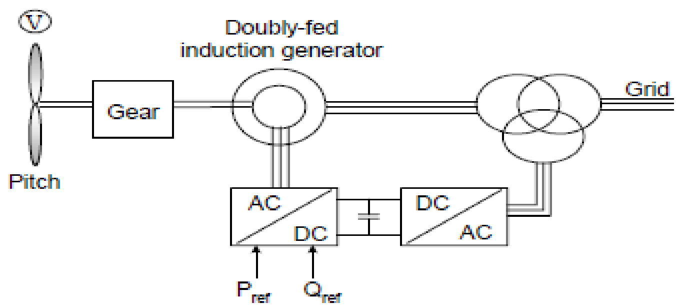
Variable speed wind power conversion system

The next category is variable speed systems where pitch control is typically used. Variable speed wind turbines may be further divided into two parts, one with partially rated power electronic converters and one with fully rated power electronic converters.

Variable speed wind power conversion systems with partially rated power electronic converters



(a)



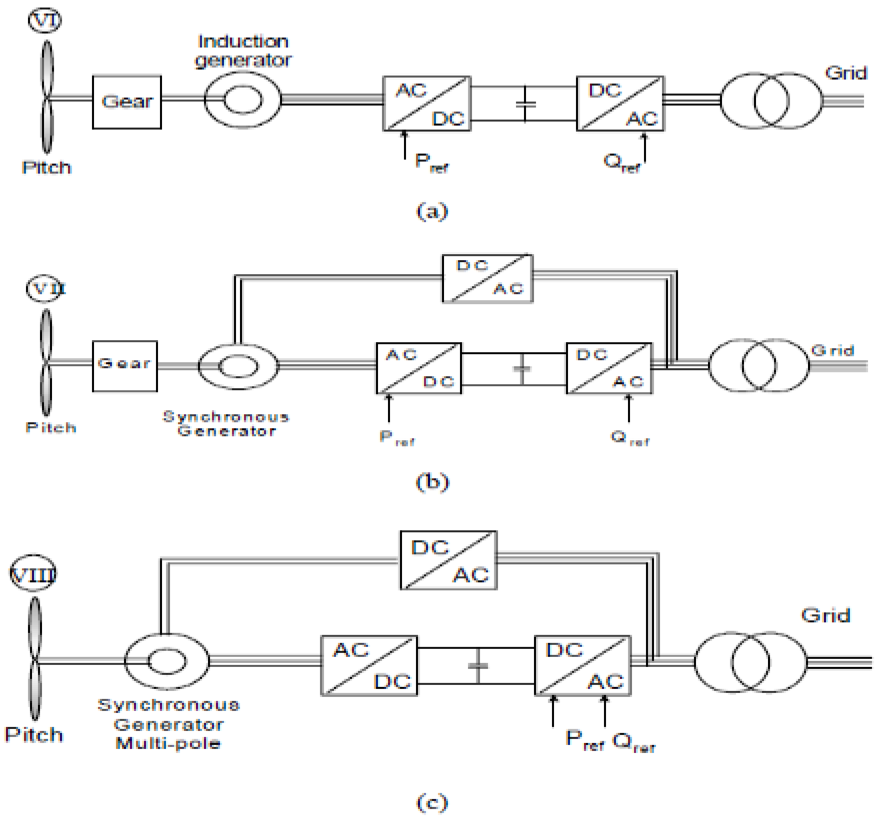
(b)

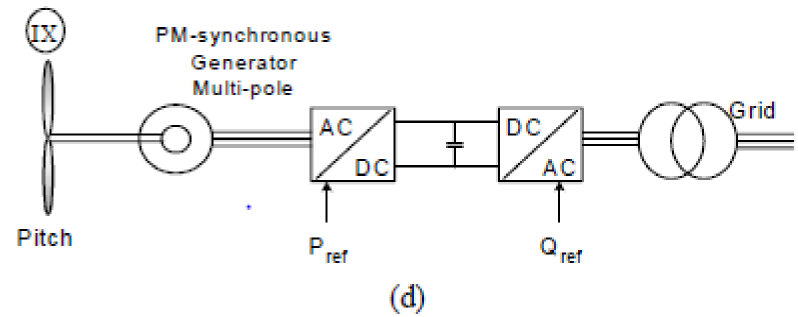
Wind turbine topologies with partially rated power electronics and limited speed range,
(a) Rotor-resistance converter (System IV)
(b) Doublyfed induction generator (System V).

Figure shows wind turbines with partially rated power electronic converters that are used to obtain an improved control performance.

Variable speed wind power conversion systems with fully rated power electronic converters

- **The wind turbines with a full-scale power converter between the generator and grid give extra losses in the power conversion but it may be gained by the added technical performance. Figure shows four possible solutions with full-scale power converters.**





Wind turbine systems with full-scale power converters.

a) Induction generator with gear (System VI)

b) Synchronous generator with gear (System VII)

c) Multi-pole synchronous generator (System VIII)

d) Multi-pole permanent magnet synchronous generator (System IX)

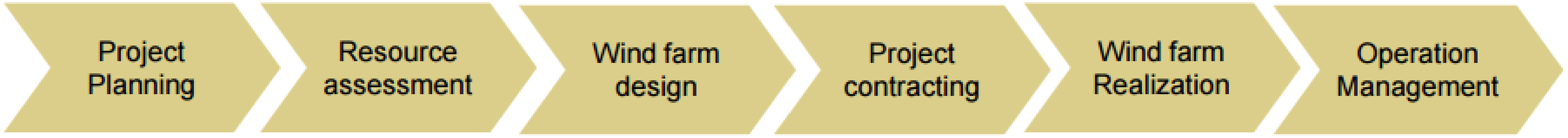
Variable speed wind power conversion system

- **All four solutions have the same controllable characteristics since the generator is decoupled from the grid by a dc-link. The power converter to the grid enables the system very fast to control active and reactive power. However, the negative side is a more complex system with a more sensitive electronic part.**

- **By introducing power electronics many of the wind turbine systems get a performance like a power plant. In respect to control performance they are faster but of course the produced real power depends on the available wind. The reactive power can in some solutions be delivered without having any wind.**

- **Wind turbines act as a real power source for the grid. They are able to be active when a fault appears at the grid and so as to build the grid voltage up again quickly; the systems have the possibility to lower the power production even though more power is available in the wind and thereby acting as a rolling capacity. Finally, some are able to operate in island operation in the case of a grid collapse.**

PROJECT CYCLE IN WIND PROJECT DEVELOPMENT



Project Planning

- Wind mapping
- Constraint mapping
- Site screening
- Economical feasibility

Resource assessment

- Wind measurements
- Resource analysis
- Site classification (/assessment / compatibility)

Wind farm design

- Wind turbine type assessment
- park lay-out (micrositing)
- Yield assessment
- Grid connection design
- Impact studies
- Permitting and consent
- Balance of plant design

Project contracting

- Uncertainty anlysis and bankable reporting
- Tendering (EPC, O&M, PPA, insurance)
- Bid evaluation
- Contract negotiations
- Risk assessment and mitigation
- Financial and planning

Wind farm Realization

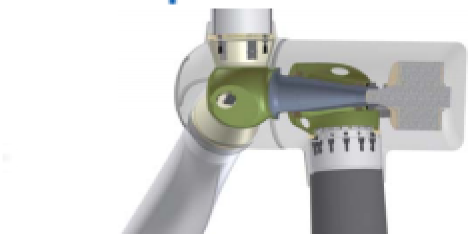
- Quality control
- Commissioning
- Provisional & final acceptance
- Technical assistance
- Project management
- Site supervision

Operation Management

- Wind farm inspections
- Performance monitoring
- short term forecasting

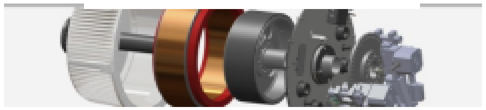
- Improving Performance:
  - Capacity: higher heights, larger blades, superconducting magnets
  - Capacity Factor: higher heights, advanced control methods (individual pitch, smart-blades), site-specific designs
- Reducing Costs:
  - Weight reduction: 2-blade designs, advanced materials, direct drive systems
  - Offshore wind: foundations, construction and maintenance

American Superconductor®



VERGNET GROUPE

Northern POWER SYSTEMS



- 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