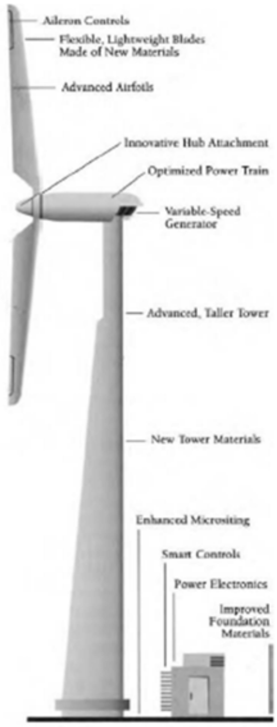
Faculty of Engineering and Technology

Department of Chemical Engineering

University Of Jordan



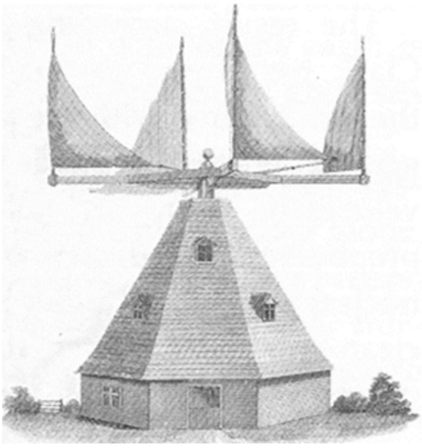
Fuel and Energy

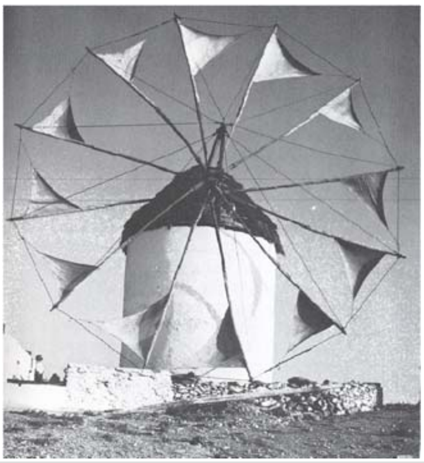
Wind Energy

Dr.-Eng. Zayed Al-Hamamre

Content

- **Wind Resource & Power**
- **Windmill: Types, Design, Size and Evolution**
- **Economics consideration**
- **Typical Concerns**





Wind Power- What is it?

- All renewable energy (except tidal and geothermal power), ultimately comes from the sun

- The earth receives 1.74 x 10^{17} watts of power (per hour) from the sun

- About one or 2 percent of this energy is converted to wind energy (which is about 50-100 times more than the energy converted to biomass by all plants on earth

- Differential heating of the earth's surface and atmosphere induces vertical and horizontal air currents that are affected by the earth'srotation and contours of the land → WIND. ~ e.g.: Land Sea Breeze Cycle
- Winds are influenced by the ground surface at altitudes up to 100 meters.
- Wind is slowed by the surface roughness and obstacles.
- When dealing with wind energy, we are concerned with surface winds.

Wind Power- What is it?

- A wind turbine obtains its power input by converting the force of the wind into a torque (turning force) acting on the rotor blades.

- The amount of energy which the wind transfers to the rotor depends on the density of the air, the rotor area, and the wind speed.

- The kinetic energy of a moving body is proportional to its mass (or weight). The kinetic energy in the wind thus depends on the density of the air, i.e. its mass per unit of volume.
  In other words, the "heavier" the air, the more energy is received by the turbine.

- At 15° Celsius air weighs about 1.225 kg per cubic meter, but the density decreases slightly with increasing humidity.

Wind Power- What is it?

- A typical 600 kW wind turbine has a rotor diameter of 43-44 meters, i.e. a rotor area of some 1,500 square meters.
- The rotor area determines how much energy a wind turbine is able to harvest from the wind.
- Since the rotor area increases with the square of the rotor diameter, a turbine which is twice as large will receive $2^2 = 2 \times 2 =$ four times as much energy.
- To be considered a good location for wind energy, an area needs to have average annual wind speeds of at least 12 miles per hour.

The Wind Resource

- Wind is the approximate horizontal movement of air caused by differential heating of the earth's surface
- Air rises from the warmer surfaces and cooler is drawn in from the surrounding areas.

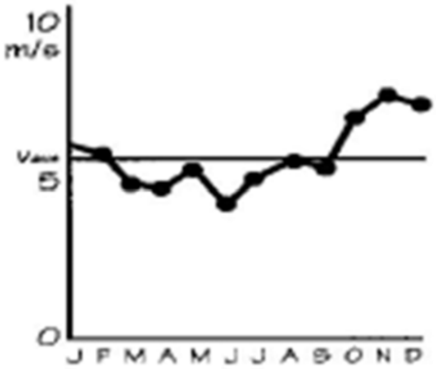
- Wind is affected by topography—wind speed is affected by roughness and obstacles such as buildings and hills.
- Speed increases when approaching the obstacle and decreases and may separate and become turbulent of the downstream side

The Wind Resource

- Wind turbines are often placed near the top of hills and ridges and well away from buildings and other structures

- The "windiness" of a particular site is described in terms of the Annual Average Wind Speed

Wind Regime Description	Annual Average wind speed (m/s@10m)	Typical Capacity Factor
Poor	<4.0	0.25
Fair	4.0 - 5.0	0.3
Good	5.0 - 6.0	0.35
Very Good	6.0 -7.0	0.4
Excellent	>7.0	0.45



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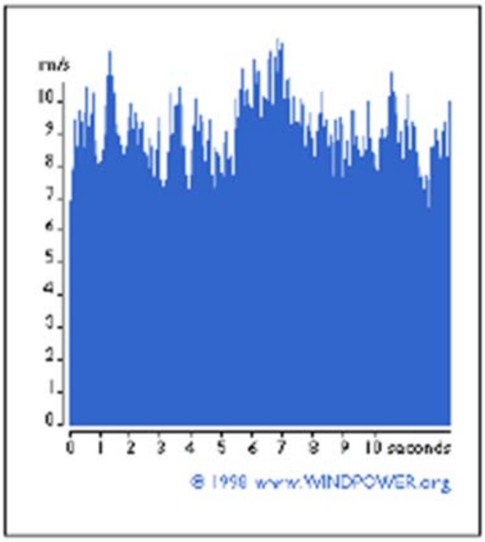
The Wind Resource

- Wind speed varies with time over several orders of magnitude
- Rapid fluctuations in wind speed are called turbulence and may increase the structural and dynamic stresses on the wind turbine components
- Thus it is not desirable to install turbines in areas of high turbulence



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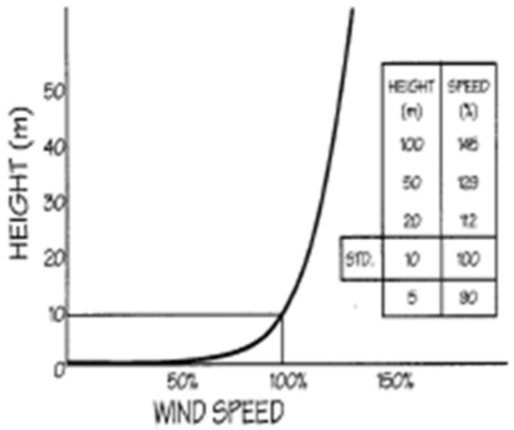
The Wind Resource

- Near the earths surface wind speed is reduced l friction
- Wind turbines operate in the earth's boundary layer
- The higher the wind turbine tower, the greater the annual average wind speed



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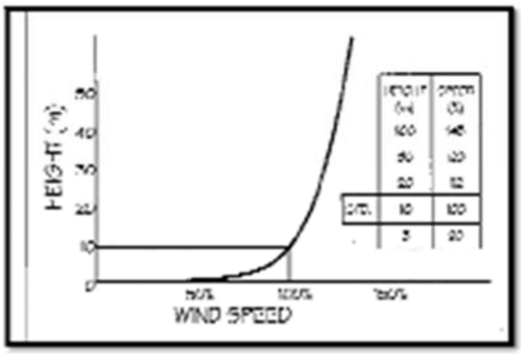
The Wind Resource

Wind speed is related to height by

$$\frac{V_2}{V_1} = \left(\frac{H_2}{H_1}\right)^{\alpha}$$



The exponent α depends on the type and roughness of the terrain.

For flat land without major obstructions, α = 0.16 and wind speed increase 12% for every doubling of height.

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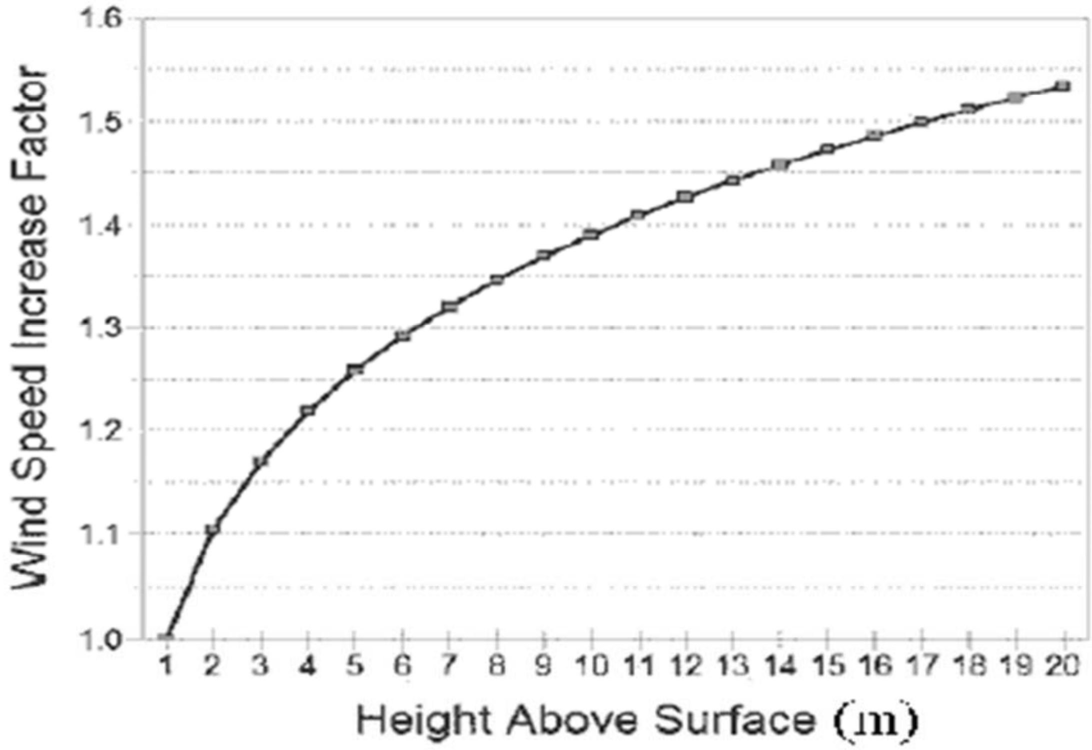
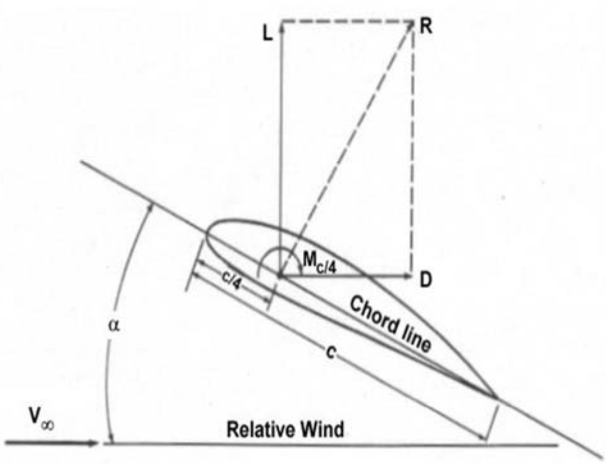
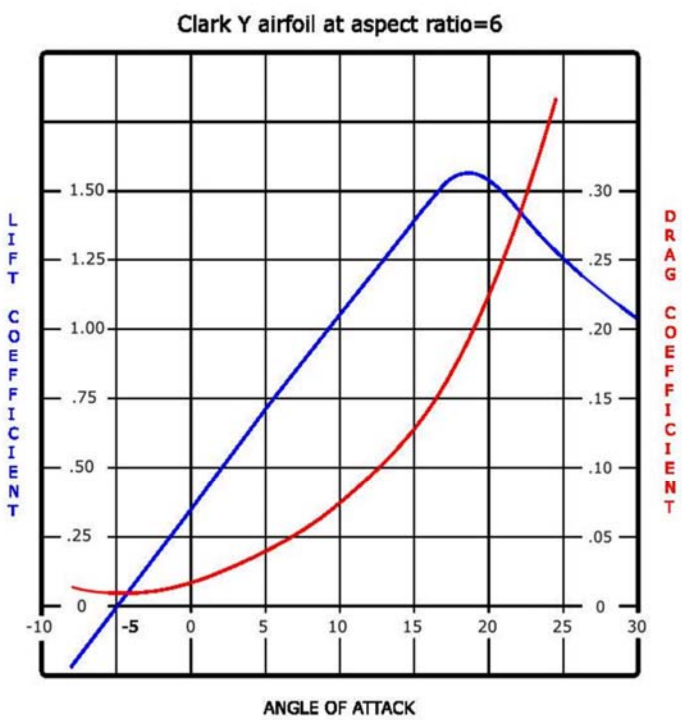
The Wind Resource



Power and Energy in Wind

Lift and drag forces





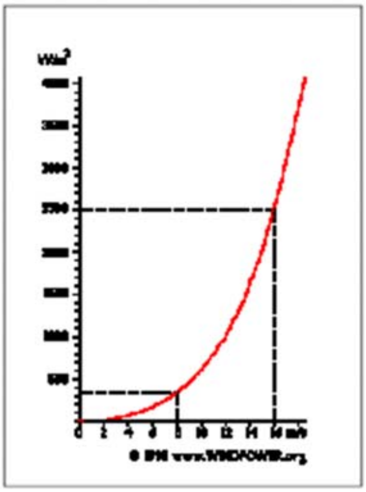
Power and Energy in Wind

- The Kinetic Power in a moving air stream is given by

$$KP = \frac{1}{2} \rho A V^3$$

Where
KP = Power in Wind, (Watts)
ρ = Air density
(1.225 kg/m³ at 15°C, 1.0132 bar)
A= Cross-sectional flow area (m²)
V = Wind speed (m/s)

Note: Power is proportional to the CUBE of wind speed



- The power in wind is proportional to the cubic wind speed (v^3).
- Kinetic energy of an air mass is proportional to v^2
- Amount of air mass moving past a given point is proportional to wind velocity (v)

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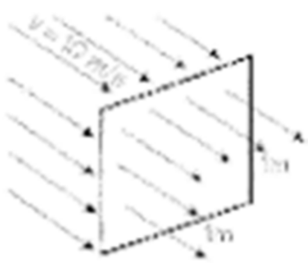
Power and Energy in Wind

- Average power is not linearly proportional to the average wind speed!

$$KP_{ave} = 6/\pi \left(\frac{1}{2} \rho A V_{ave}^{3}\right)$$



The term , $6/\pi$, accounts for the distribution of wind speed, and hence kinetic power with wind with time. Average power is not linearly proportional to the average wind speed

e,g., a 10 m/s wind blowing through a 1m² window

$$KP_{ave} = 6/\pi \left(\frac{1}{2}\, 1.225 \times 1 \times 10^3\right)$$
$$= 1170 \text{ W} = 1.17 \text{ kW}$$

- On average, good wind turbines extract about half of the theoretical maximum or 30% of the power in the airstream that passes through the rotor, thus

$$P_{ave} = 0.3\, 6/\pi \left(\frac{1}{2} \rho A V_{ave}^{3}\right)$$
$$= 0.35\ A V_{ave}^{3}$$

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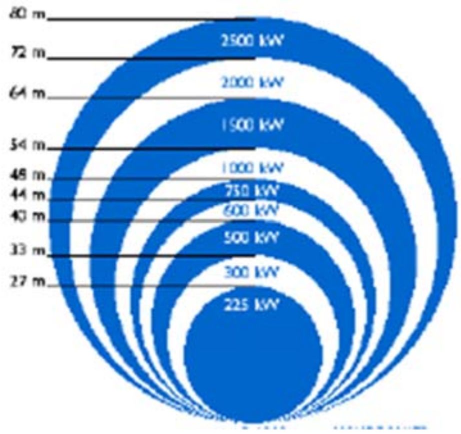
Power and Energy in Wind

- Turbine output effectively increases as the square of the diameter

D1 = 25 m, P1= 225 Kw
D2 = 50 m, P2= ?

P2 = $(50/25)^2$ x P1
= 900 kW



- Actual turbine output will vary somewhat due to specific design features and turbine performance

Power and Energy in Wind

Energy is power multiplied by time. Thus:

$$E(kWh) = \frac{P(W)}{1000} \times t(h)$$

So, the annual energy production of a wind turbine can be estimated from:

$$AEO = \frac{P_{ave} \times 8760}{1000} = 3.1\ AV_{ave}^3$$

where; AEO = Annual energy output (kWh/y)
8760 = Number of hours in a year
A = Area swept by wind turbine rotor (m²)
V_{ave} = Average wind speed (m/s)

i.e., for the above example the annual energy output would be 650 MWh/y – sufficient for 80 homes

Power and Energy in Wind: Betz Limit Model Assumptions

- Model considers a control volume analysis of a stream tube.
- The thrust over the control volume is calculated as

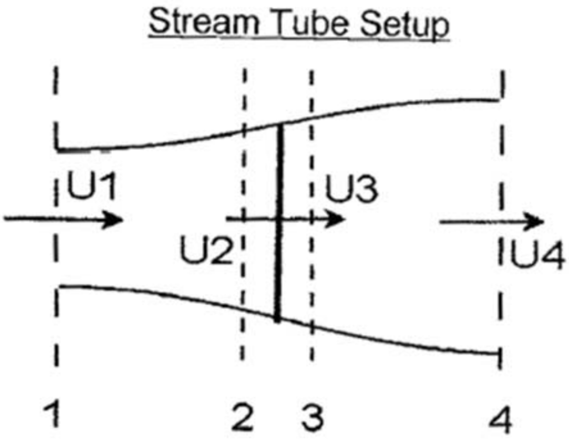
$$T = \dot{m}(U_1 - U_4)$$

- The power extracted at the rotor is

$$P = \frac{1}{2}\rho A_2 U_1^3 4a(1-a)^2$$

Where $a = \dfrac{U_1 - U_2}{U_1}$

Is the Axial Induction Factor (a) is defined as the fractional decrease in wind speed from state 1 to state 2



From B.E $p_1 + \frac{1}{2}\rho U_1^2 = p_2 + \frac{1}{2}\rho U_2^2$

$$p_3 + \frac{1}{2}\rho U_3^2 = p_4 + \frac{1}{2}\rho U_4^2$$

$$U_2 = U_1(1-a)$$

$$U_4 = U_1(1-2a)$$

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Power and Energy in Wind: Betz Limit Model Assumptions

- The power coefficient can be calculated as the power extracted by the rotor compared to the power available in the wind:

$$C_P = \frac{\text{power extracted}}{\text{power available}} = \frac{\frac{1}{2}\rho A_2 U_1^3 4a(1-a)^2}{\frac{1}{2}\rho U_1^3 A}$$

$$\boxed{C_P = 4a(1-a)^2}$$

- The maximum possible power coefficient (Betz Limit) is

$$C_P' = 4a(1-a)^2 - 8a(1-a)$$

When $C_P' = 0$, $a = (1, \frac{1}{3})$.

$$C_{P,max} = 4a(1-a)^2 = 4\left(\frac{1}{3}\right)\left(1-\left(\frac{1}{3}\right)\right)^2 \approx \boxed{0.5926}$$

- **The Betz limit represents the highest theoretical efficiency that can be achieved for this ideal case**

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Power and Energy in Wind: Betz Limit Model Assumptions

- Mechanical inefficiencies in the rest of the system will also reduce the amount of power that can be extracted from the wind.

$$\eta_{overall} = \frac{P_{out}}{\frac{1}{2}\rho A U^3} = \eta_{mech} C_P \Rightarrow P_{out} = \frac{1}{2}\rho A U^3 \left(\eta_{mech} C_P\right)$$

Rated Power Output:

$$P_{eR} = C_{PR}\eta_{mR}\eta_{gR}\frac{\rho}{2}Au_R^3 \qquad (W)$$

$$P_e = C_P\eta_m\eta_g P_W \qquad (W)$$

C_P = Power Coefficient

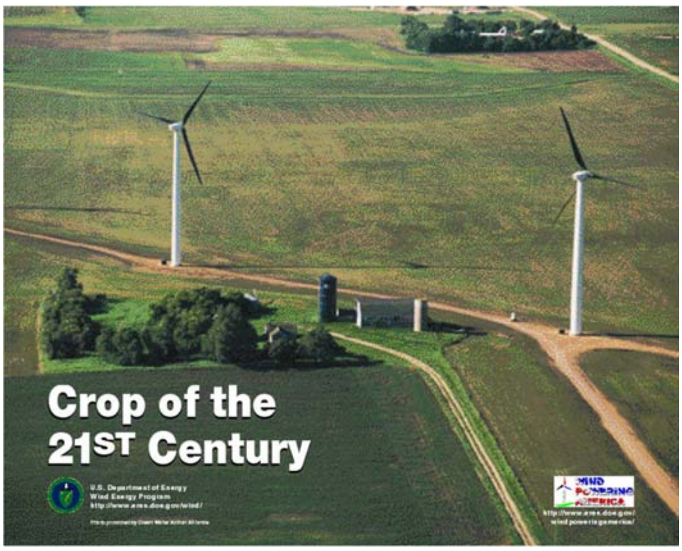
η_m = Transmission Efficiency

η_g = Generator Efficiency (or pump, compressor, ect...)

$$\eta_o = C_{PR}\eta_{mR}\eta_{gR}$$

Drivers for Wind Power

- Declining Wind Costs
- Fuel Price Uncertainty
- Federal and State Policies
- Economic Development
- Green Power
- Energy Security



When the wind doesn't blow…

- **Do fossil-fired generating units have to be kept running on a standby basis in case the wind dies down?**

- No. Wind speeds rise and fall gradually and the system operator has time to move other plants on and off line as needed.
- A 100-MW wind plant requires about 2 MW of conventional capacity to compensate for changes in wind.
- Wind can reliably provide 20% or more of our electricity.

Windmill Design

- A Windmill captures wind energy and then uses a generator to convert it to electrical energy.
- The design of a windmill is an integral part of how efficient it will be.
- When designing a windmill, one must decide on the size of the turbine, and the size of the generator.

Sizes and Applications

Small (≤10 kW)

Homes

Farms

Remote Application

Intermediate

(10-250 kW)

Village Power

Hybrid Systems

Distributed Power

Large (660 kW - 2+MW)

Central Station Wind Farms

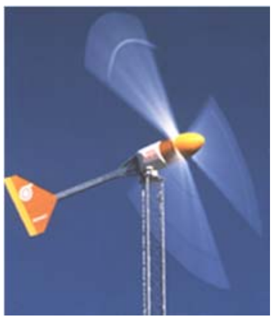
Distributed Power

Community Wind

Large and Small Wind Turbines

Large Turbines (600-2000 kW)

- Installed in “Windfarm” arrays totaling 1 - 100 MW
- $1,300/kW
- Designed for low cost of energy (COE)
- Requires 6 m/s (13 mph) average wind speed
- Value of Energy: $0.02 - $0.06 per kWh

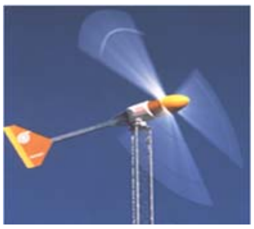


Small Turbines (0.3-100 kW)

- Installed in “rural residential” on-grid and off-grid applications
- $2,500-$8,000/kW
- Designed for reliability / low maintenance
- Requires 4 m/s (9 mph) average wind speed
- Value of energy: $0.06 - $0.26 per kWh

Small Wind Turbines

- Blades: Fiber-reinforced plastics, fixed pitch, either twisted/tapered, or straight (pultruded)
- Generator: Direct-drive permanent magnet alternator, no brushes, 3-phase AC, variable-speed operation
- Designed for:
  – Simplicity, reliability
  – Few moving parts
  – Little regular maintenance required


10 kW


50 kW


400 W


900 W

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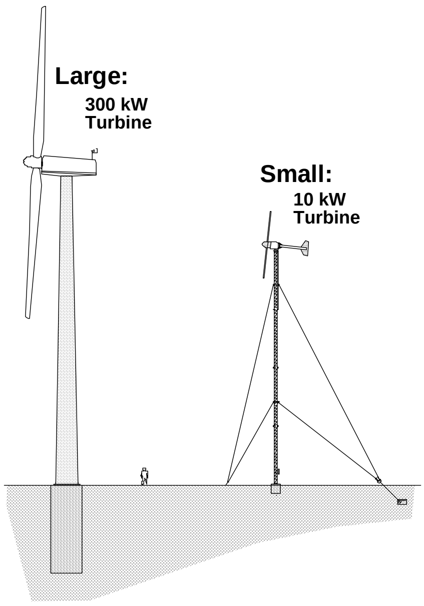
Large and Small Wind Turbines are Different

- **Large Turbines (500-1500 kW)**
  - **Installed in "Windfarm" Arrays Totaling 1 - 100 MW**
  - **$1,000/kW; Designed for Low Cost of Energy**
  - **Requires 6 m/s (13 mph) Average Sites**
- **Small Turbines (0.3-100 kW)**
  - **Installed in "Rural Residential" On-Grid and Off-Grid Applications**
  - **$2,500-5,000/kW; Designed for Reliability / Low Maintenance**
  - **Requires 4 m/s (9 mph) Average Sites**



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Turbine Evolution

Used for

Pumping water

Grinding grain

Mainly used for

Generating Electricity

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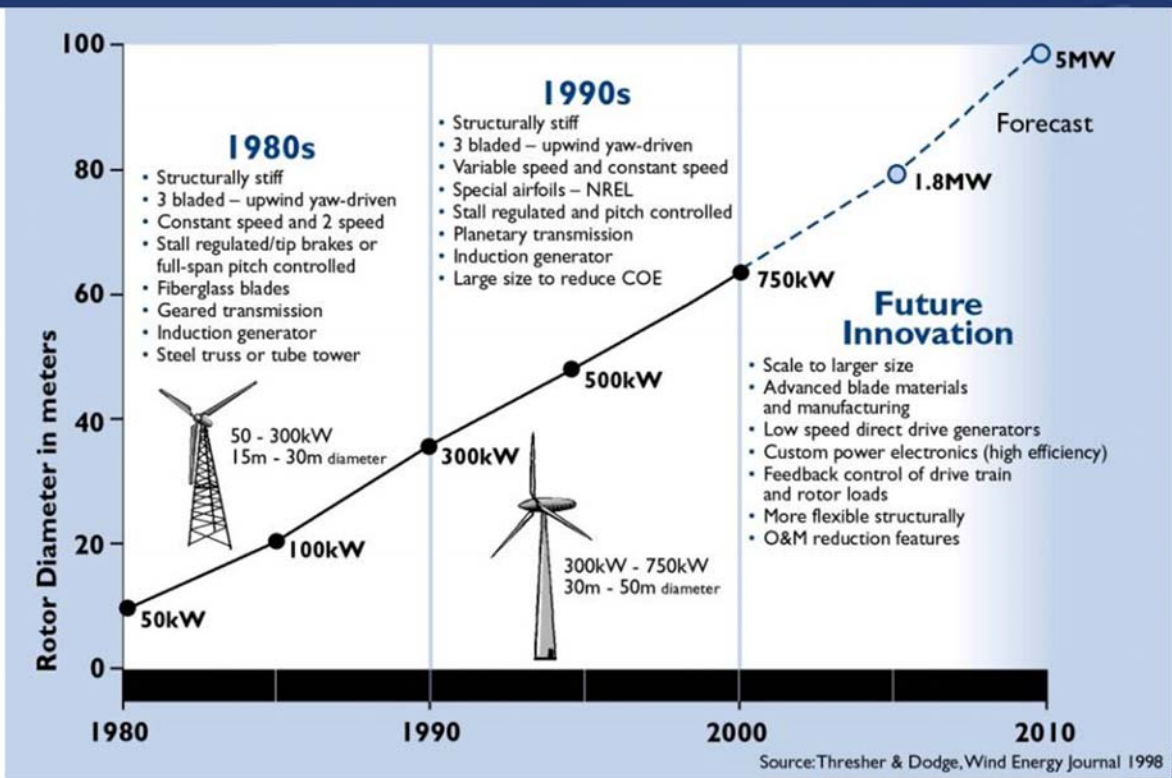
Turbine Evolution



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Types of turbines

VAWT (Vertical Axis Wind Turbine)

- Drag is the main force
- Nacelle is placed at the bottom
- Yaw mechanism is not required
- Lower starting torque
- Difficulty in mounting the turbine
- Unwanted fluctuations in the power output

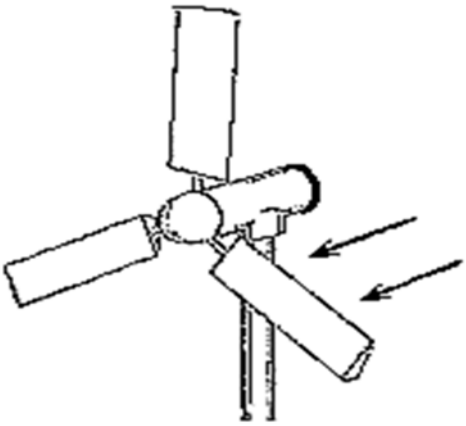
Types of turbines

HAWT (Horizontal Axis Wind Turbine)

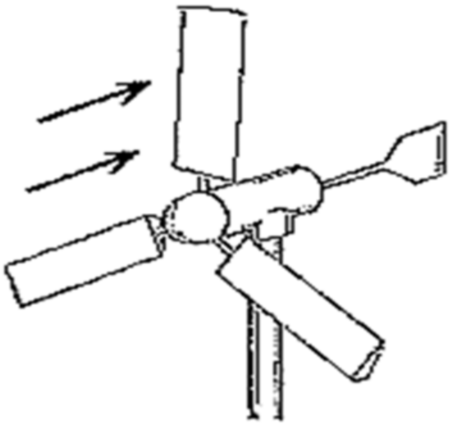
- Lift is the main force
- Much lower cyclic stresses
- 95% of the existing turbines are HAWTs
- Nacelle is placed at the top of the tower
- Yaw mechanism is required

Two types of HAWT

DOWNWIND TURBINE



UPWIND TURBINE



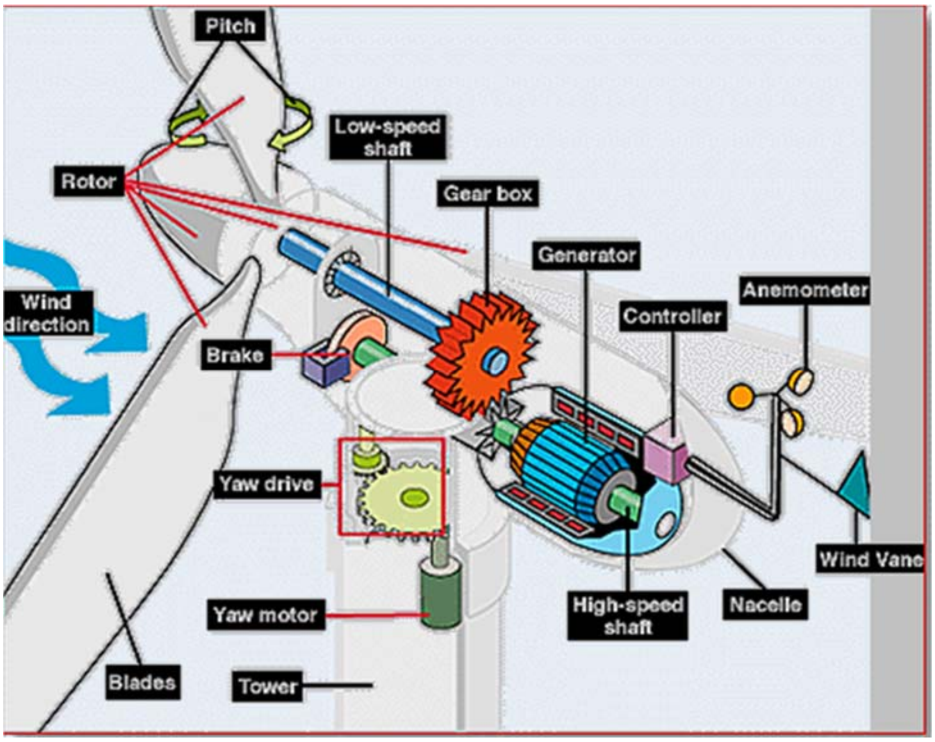
Two types of HAWT

Counter Rotating HAWT

- Increase the rotation speed
- Rear one is smaller and stalls at high wind speeds
- Operates for wider range of wind speeds

- More wind speeds
- Less noise pollution
- Less visual impact
- Difficult to install and maintain
- Energy losses due long distance transport

A Typical HAWT



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Turbine design and construction

- Blades
  - ➢ Material used
  - ➢ Typical length
- Tower height
  - ➢ Heights twice the blade length are found economical

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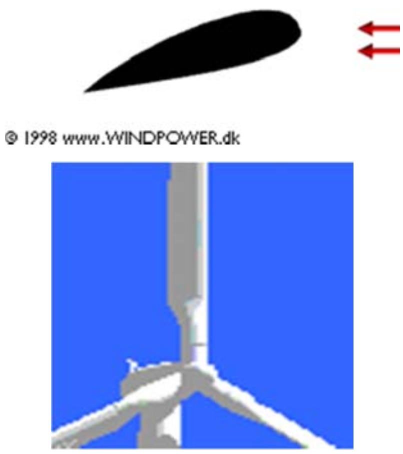
Turbine design and construction

- Number of blades
  - Three blade HAWT are most efficient
  - Two blade turbines don’t require a hub
  - As the number increases; noise, wear and cost increase and efficiency decreases
  - Multiple blade turbines are generally used for water pumping purposes.

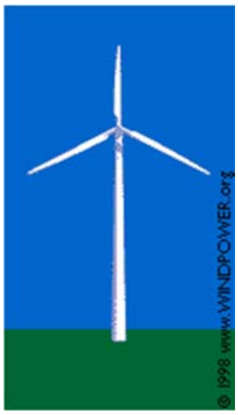
Turbine design and construction

- Rotational control
  - Maintenance
  - Noise reduction
  - Centripetal force reduction
  - Mechanisms
    - Stalling
    - Furling



Turbine design and construction

- Yaw Mechanism
  - To turn the turbine against the wind
  - Yaw error and fatigue loads
  - Uses electric motors and gear boxes
- Wind turbine safety
  - Sensors – controlling vibrations
  - Over speed protection
    - Aero dynamic braking
    - Mechanical braking



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Wind Turbine Selection

- Rotor diameters may vary somewhat for a given power, because many manufacturers optimize their machines to local wind conditions.
- A larger generator requires more power (i.e. strong winds) to start. So if you install a wind turbine in a low wind area you will actually maximize annual output by using a fairly small generator for a given rotor size (or a larger rotor size for a given generator).
- For example, for a 600 kW machine rotor diameters may vary from 39 to 48 m (128 to 157 ft.) The reason why you may get more output from a relatively smaller generator in a low wind area is that the turbine will be running more hours during the year.

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Wind Turbine Selection

Reasons for Choosing Large Turbines

- There are economies of scale in wind turbines, i.e. larger machines are usually able to deliver electricity at a lower cost than smaller machines. The cost of foundations, road building, electrical grid connection, plus a number of components in the turbine (the electronic control system etc.), are somewhat independent of the size of the machine.
- Larger machines are particularly well suited for offshore wind power. The cost of foundations does not rise in proportion to the size of the machine, and maintenance costs are largely independent of the size of the machine.
- In areas where it is difficult to find sites for more than a single turbine, a large turbine with a tall tower uses the existing wind resource more efficiently.
- Large machines, however, will usually have a much lower rotational speed than small machines, i.e., one large machine really does not attract as much attention as many small, fast moving rotors.

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Wind Turbine Selection

Reasons for Choosing Smaller Turbines

- Local electrical grids may be too weak to handle the output from a large machine. This may be the case in remote parts of the electrical grid with low population density and little electricity consumption in the area.
- There is less fluctuation in the electricity output from a wind park consisting of a number of smaller machines, since wind fluctuations occur randomly, and therefore tend to cancel out.
- Costs for large cranes and building adequate roads to carry the turbine components may make smaller machines more economic in some areas.
- Several smaller machines spread the risk in case of temporary machine failure, e.g. due to lightning strikes.
- Aesthetical landscape considerations may sometimes dictate the use of smaller machines.

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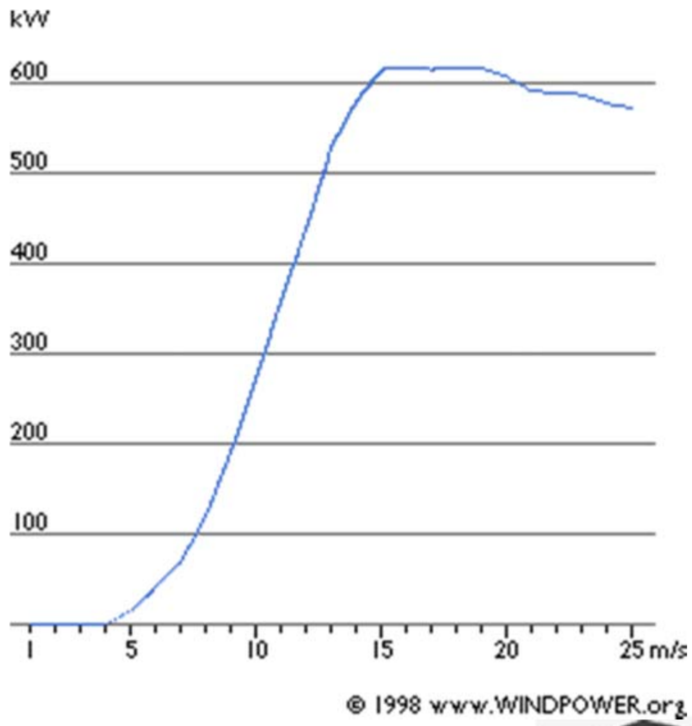
Wind Turbine Selection

- The power curve of a wind turbine indicates the electrical power output for the turbine at different wind speeds.
- The graph shows a power curve for a typical 600 kW wind turbine. Power curves are found by field measurements of power output versus wind speed. An anemometer is placed on a mast reasonably close to the wind turbine to measure the wind speed.



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Turbine Efficiency (Power Coefficient)

- The power coefficient tells you how efficiently a turbine converts the energy in the wind to electricity. Very simply, we just divide the electrical power output by the wind energy input to measure how efficient a wind turbine is.
- The graph shows a power coefficient curve for a typical wind turbine. The average efficiency is about 20 per cent. It varies with the wind speed, but is largest at around 9 m/s.
- At low wind speeds efficiency is not as important because there is not much energy to harvest.
- By design, at high wind speeds, the turbine wastes excess energy above the generator rating

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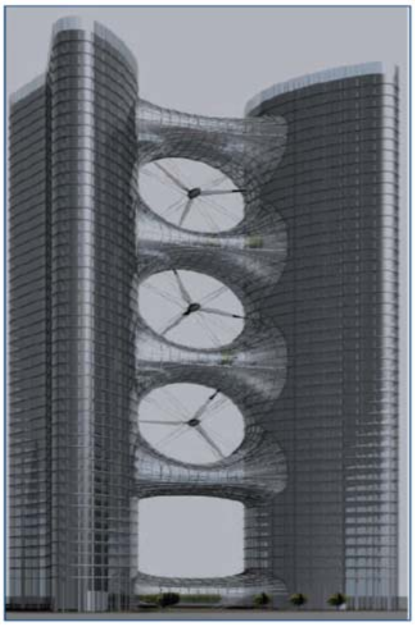
Turbine Efficiency (Power Coefficient)

- Wind turbines are designed to produce electrical energy as cheaply as possible. Wind turbines are therefore generally designed so that they yield maximum output at wind speeds around 15 m/s.
- Its does not pay to design turbines that maximize their output at stronger winds, because such strong winds are rare.
- In case of stronger winds it is necessary to waste part of the excess energy of the wind in order to avoid damaging the wind turbine.
- All wind turbines are therefore designed with some sort of power control.

Improvements

Concentrators



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Future Wind Turbines

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Disc type wind turbine

- Much more efficient than HAWT
- Requires less height
- Low noise
- Works in any wind direction

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Economics consideration

Determining Factors

- Wind Speed and
- Turbine design, size, model and construction (tower height)
- Rated capacity of the turbine
- Exact Location
- Improvements in turbine design
- Plant Size: equipment, installation and O&M economies of scale
- Capital

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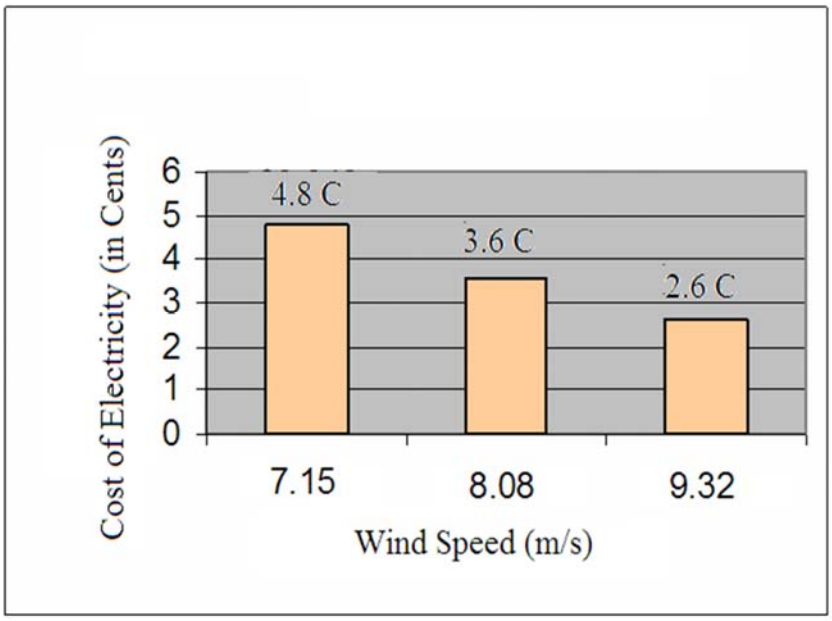
Economics consideration

Wind Speed Matters



- Assuming the same size project, the **better** the wind resource, the lower the cost.

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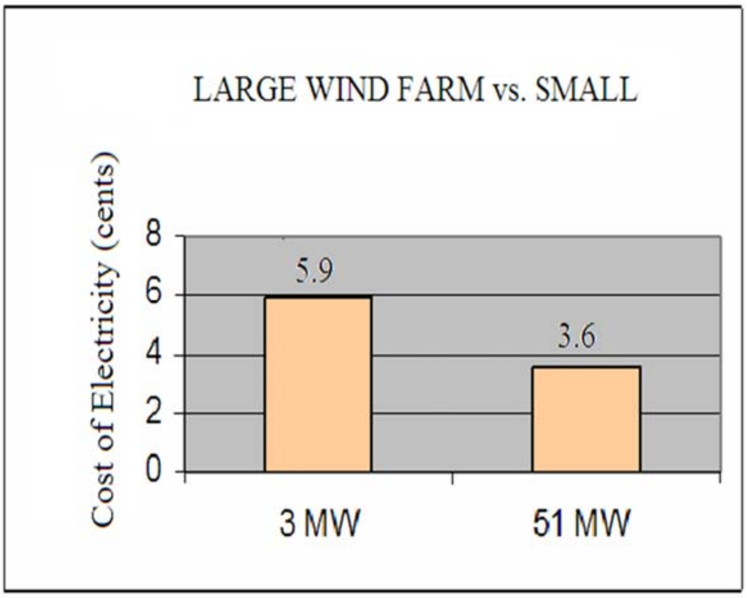
Economics consideration

Size Matters



- Assuming the same wind speed of 8.08 m/s, a large wind farm is more economical

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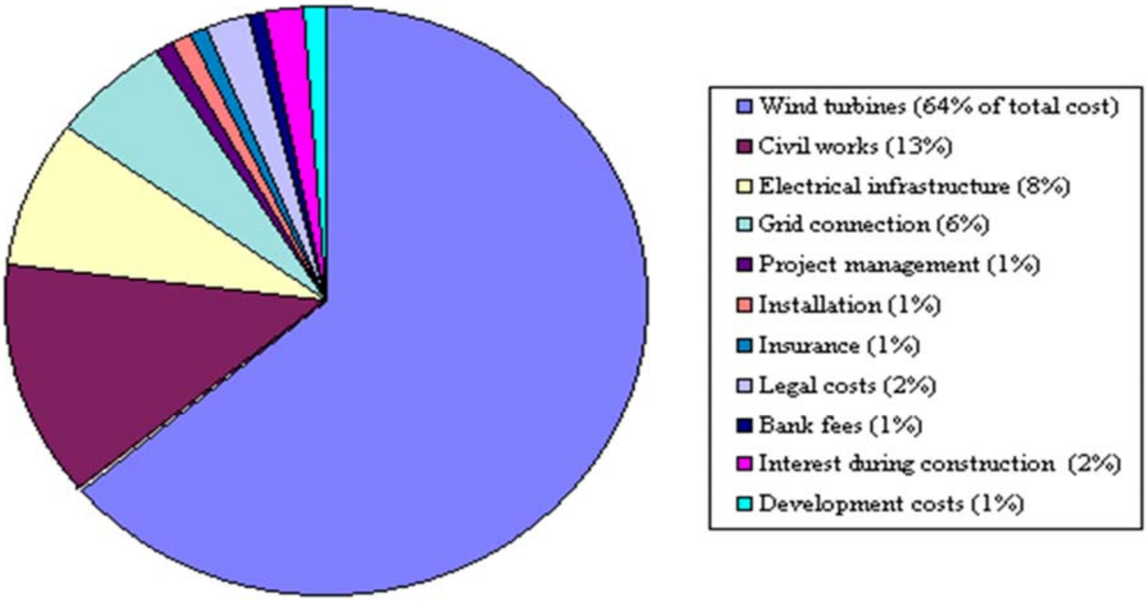
Economics consideration

Overall cost distribution



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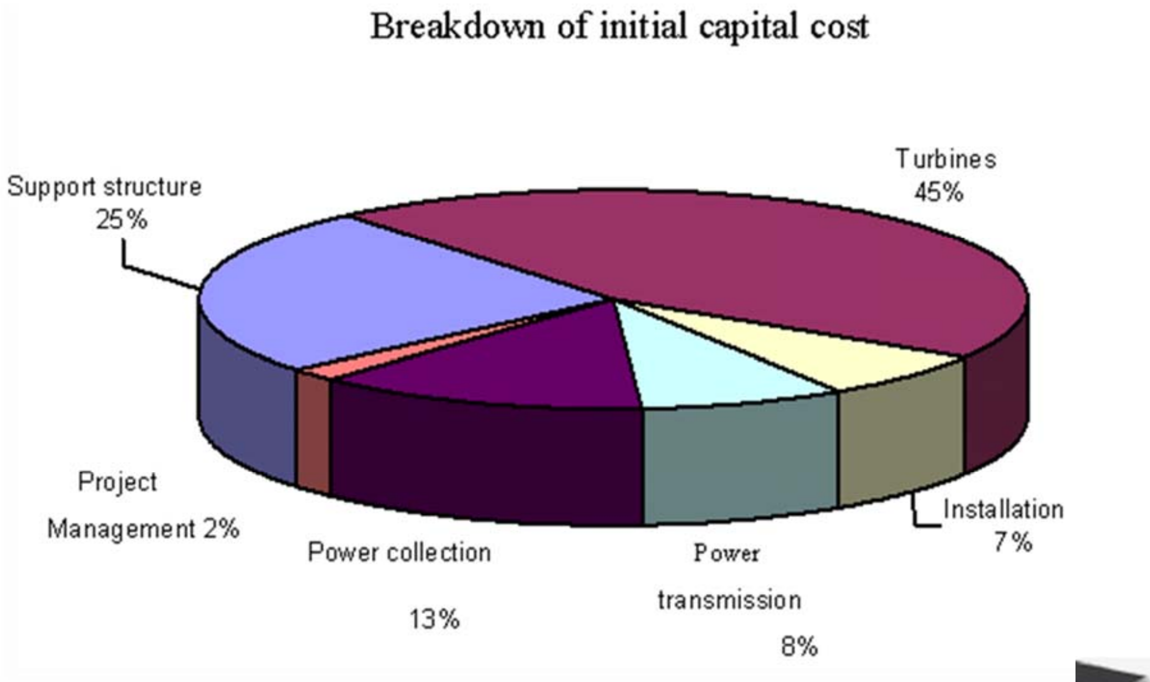
Economics consideration

Break down of capital cost



Energy Cost Trend

1979: 40 cents/kWh

2000:
4 - 6 cents/kWh

- Increased Turbine Size
- R&D Advances
- Manufacturing Improvements

2004:
3 – 4.5 cents/kWh

Energy Cost Trend

- A typical 600 kW turbine costs about $450,000.
- Installation costs are typically $125,000.
- Therefore, the total costs will be about $575,000.
- The average price for large, modern wind farms is around $1,000 per kilowatt electrical power installed.
- Modern wind turbines are designed to work for some 120,000 hours of operation throughout their design lifetime of 20 years. (13.7 years non-stop)
- Maintenance costs are about 1.5-2.0 percent of the original cost, per year.

Typical cost statistics

- Size: 51 MW
- Wind Speed: 13-18 miles/hour
- Capital cost: $ 65 million ($1300/MW)
- Annual production: 150 million kW-hr
- Electricity costs: 3.6-4.5 cents
- Payback period: 20 years

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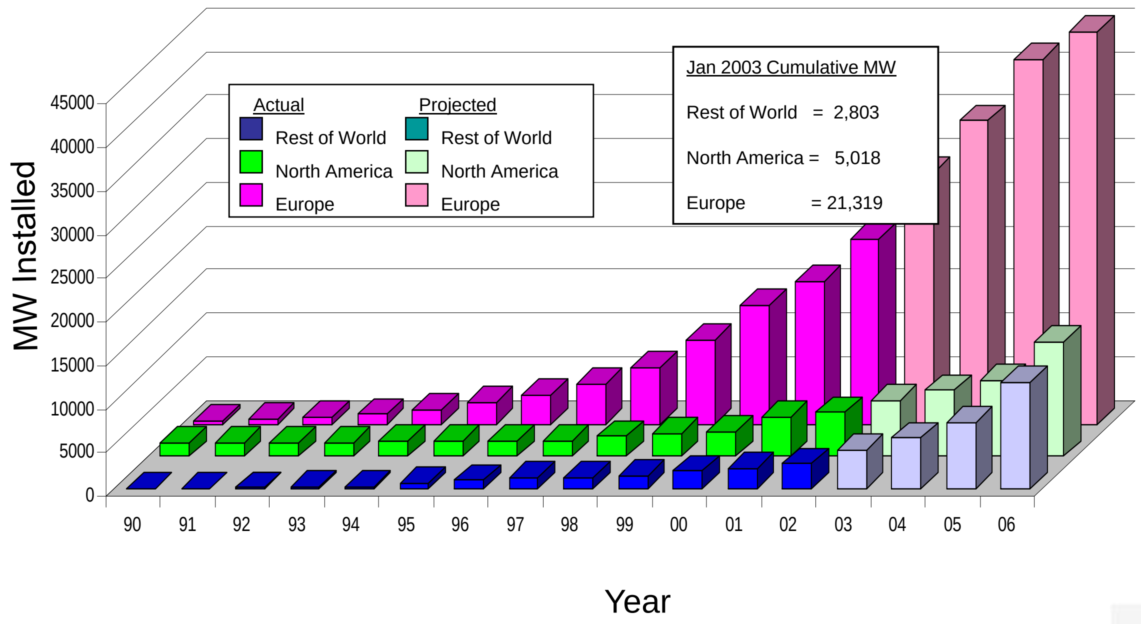
Growth of Wind Energy Capacity Worldwide



➢Sources: BTM Consult Aps, March 2001
➢Windpower Monthly, January 2003

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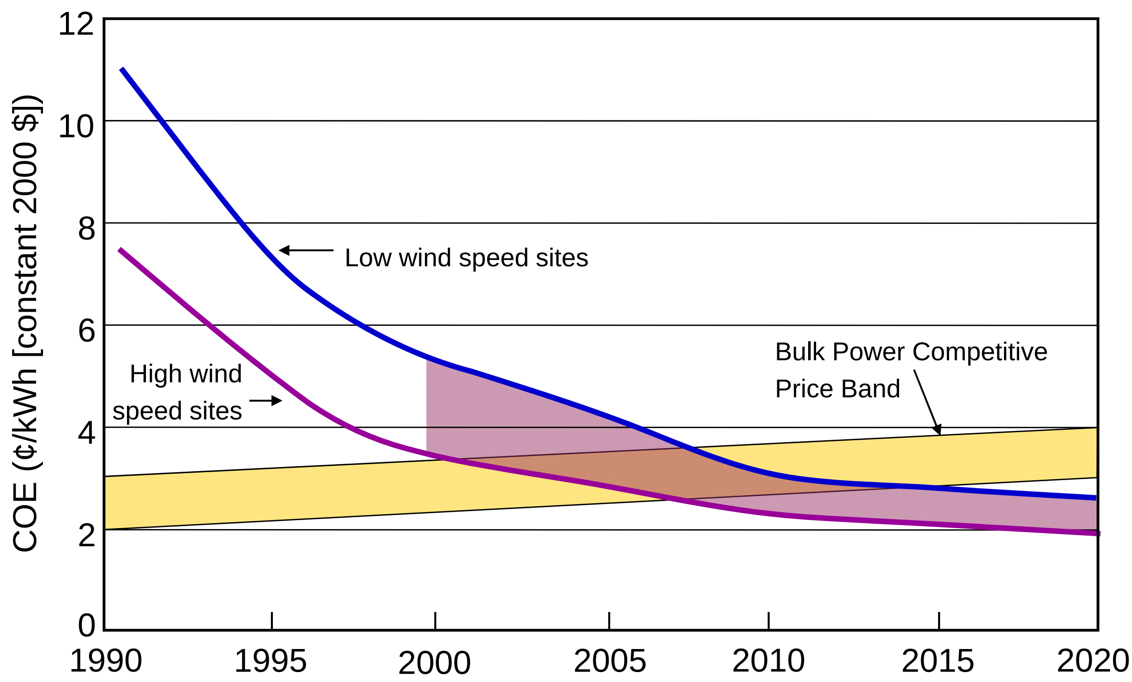
Wind Cost of Energy



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Typical Concerns

- Visual impact
  - Off shore turbines
  - Arrangement
- Avian concerns
  - Suitable choice of site
  - Using tubular towers instead of lattice tower
  - Using radars

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Typical Concerns

- Changes in wind patterns
  - Reducing turbulence
- Intermittent
  - Coupling with hydro or solar energy
- TV, microwave, radar interference
  - Switching from conducting material to non-conducting and composite material
- Noise
  - Varies as 5^{th} power of relative wind speed
  - Streamlining of tower and nacelle
  - Acoustic insulation of nacelle
  - Specially designed gear box
  - Use of upwind turbines
  - Reducing angle of attack
  - Low tip speed ratios

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Typical Concerns

Electrical power quality



- Generally not a concern for low “penetration”
- Weak grids and grid reinforcement
  - Problems may occur if a turbine is connected to a weak electrical grid, which can be reinforced.
  - Power quality problems caused by wind farms are the exact mirror-image of connecting a large electricity user, (e.g. a factory with large electrical motors) to the grid.
- Electrical flicker
  - Flicker = short lived voltage variations in the electrical grid which may cause light bulbs to flicker.
  - Flicker may occur if a wind turbine is connected to a weak grid.
  - Flicker can be reduced with proper turbine design.

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Typical Concerns

- Modern small (residential) wind turbines will not interfere with communication signals.
  - The materials used to make such machines are non-metallic (composites, plastic, wood).
  - Small turbines are too small to create electromagnetic interference (EMI) by "chopping up" a signal.
- Large wind turbines can interfere with radio or TV signals if a turbine is in the "line of sight" between a receiver and the signal source. Alleviate the problem by:
  - improving the receiver's antenna
  - installing relays to transmit the signal around the wind farm

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Lifetime environmental impact

- Manufacturing wind turbines and building wind plants does not create large emissions of carbon dioxide.
- When these operations are included, wind energy's CO_2 emissions are quite small:
  - about 1% of coal, or
  - about 2% of natural gas (per unit of electricity generated).
- Noise used to be a very serious problem for the wind energy industry.
  - annoying from as much as a mile away
- Aerodynamics and soundproofing have been improved significantly.
- Wind turbines operate when the wind is blowing, which tends to be louder than turbine noise.
- A modern operating wind farm at a distance of 750 to 1,000 feet is no noisier than a kitchen refrigerator or a moderately quiet room.

Lifetime environmental impact

- Wind energy is pollution free and nature friendly
- Wind energy has very good potential and it is the fastest growing energy source
- The future looks bright for wind energy because technology is becoming more advanced and windmills are becoming more efficient