Turbine Design I

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Outline

- Basic turbine designs
- Turbine loads and blades
- Design for noise
- Design trade-offs

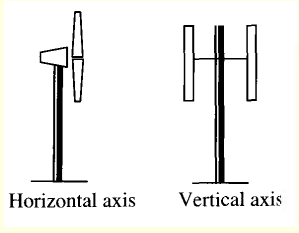
Wind Turbines

Wind Farm

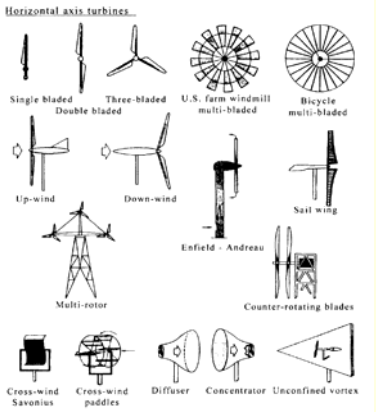
Wind Turbine

Turbine Classification: Axis Direction

- Horizontal axis
- Vertical axis



Mathew (2006)



Horizontal Axis

Eldridge (1980)

New Design Example: WindCube

Green Energy Technologies http://www.getsmartenergy.com/

- ✓ Small in size compared to the standard horizontal WT
- ✓ Designed for roof placement in urban and rural areas
- ✓ Power amplification
- ✓ 22 x 22 x 12 feet in size,
- ✓ 60kW output
- ✓ Cut-in speed 5m/h
- ✓ Annual power of 160,000 kWh at average wind speed of 15 mph

Equivalent to 50 feet diameter horizontal WT rotor

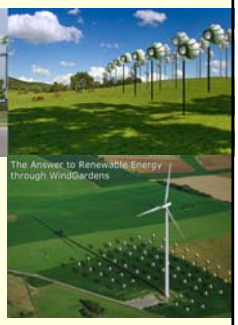
WindCube

Combining existing design concepts works

Examples: Residential WTs

Southwest Windpower http://www.windenergy.com

WindTamer™ Turbine



http://www.awrwindgardens.com/

Residential WT

Vertical Axis Turbine

Eldridge (1980)

Vertical Axis Turbines

WRE 007

750 W

WRE 030

3,000 W

WRE 060

6,000 W

http://www.ekosklep.ekologika.com.pl/index.php/cPath/46_87

Wind Turbine History

Wind Turbine History

Wind Turbine History

Darrieus wind turbines

Errichello and Muller, Geartech

Wind Turbine History

Errichello and Muller, Geartech

Wind Turbine History

The University of Iowa http://en.wikipedia.org Intelligent Systems Laboratory

Wind Turbine History

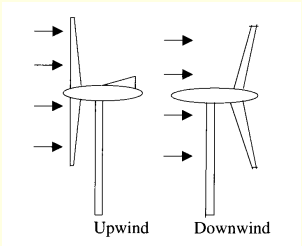
Offshore wind turbines near Copenhagen

The University of Iowa http://en.wikipedia.org Intelligent Systems Laboratory

Wind-Rotor Position

Upwind turbines
✓ Rotor is facing the wind

Downwind turbines
✓Rotor placed on the lee side of the tower



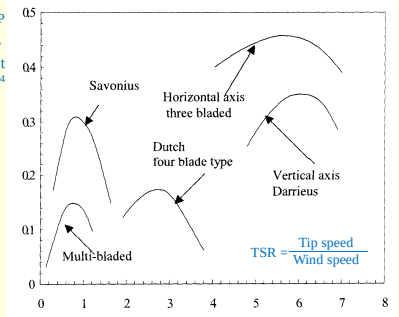
Mathew (2006)

The University of Iowa Intelligent Systems Laboratory

Why Horizontal Axis WT?

C_p

Power coefficient
(Mathew (2006), p. 14



Tip speed ratio (TSR) λ
(Mathew (2006), p. 15

Mathew (2006), p. 22

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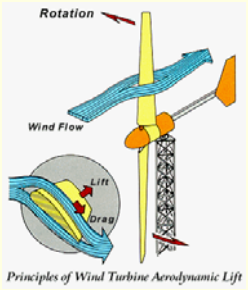
Turbine Components

http://www.galileoscientific.com/wind_energy.jpg

Operating Principles of Wind Turbines



The wind passes over both surfaces of the airfoil shaped blade.
It passes more rapidly over the longer (upper) side of the airfoil, creating a lower-pressure area above the airfoil.
The pressure differential between top and bottom surfaces results in a force, called aerodynamic lift.

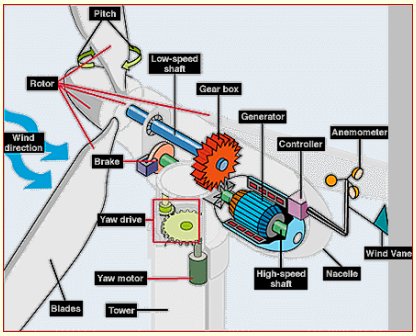
http://www.awea.org/faq/basicop.html

Operating Principles of Wind Turbines

In an aircraft wing, this forces causes the airfoil to "rise," lifting the aircraft off the ground.
Since the blades of a wind turbine are constrained to move in a plane with the hub as its center, the lift force causes rotation about the hub. In addition to lift force, a "drag" force perpendicular to the lift force impedes the rotor rotation.
A prime objective in wind turbine design is for the blade to have a relatively high lift-to-drag ratio.
This ratio can be varied along the length of the blade to optimize the turbine's energy output at various wind speeds.

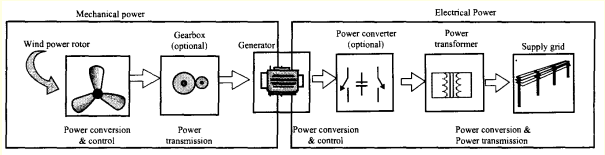
http://www.awea.org/faq/basicop.html

WT Major Components



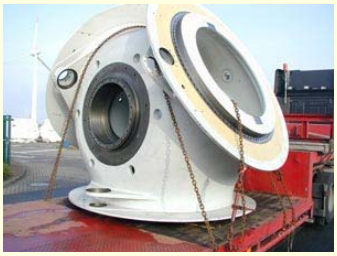
Sterzinger and Svrcek, NREP, 2004

Turbine Structure



Blaabjerg and Chen (2006)

Hub



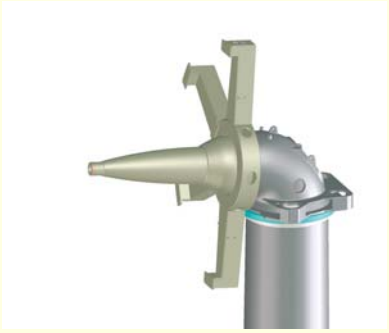
http://www.richterag.de/english/highlights/windkraftanlage

Gearless Turbine

Enercon

http://www.world-wind-energy.info/

Power Flow Concept



Enercon

http://www.world-wind-energy.info/

Upwind Turbines

Advantages:

- ✓ Upwind designs avoid the wind shade behind the tower as it faces the wind
- ✓ The vast majority of wind turbines have this design

Upwind Turbines

Disadvantages:

- ✓ The basic drawback of upwind designs is that the rotor needs to be rather inflexible, and placed at some distance from the tower (at an increased cost)
- ✓ A yaw mechanism needed to keep the rotor facing the wind
- ✓ Some wind shade in front of the tower gets created, i.e., the wind bends away from the tower before it reaches the tower itself Each time the rotor passes the tower, the power from the wind turbine minimally affected

Downwind Turbines

Advantages:

- ✓They can be built without a yaw mechanism, if the rotor and nacelle are designed so that the nacelle follow passively the wind
- ✓The rotor can be made more flexible. This helps structural dynamics and it reduces turbine weight, i.e., thinner blades bend, thus taking part of the load off the tower

Disadvantages:

- ✓ The basic drawback is the fluctuation in the wind power due to the rotor passing through the wind shade of the tower
- ✓ Larger fatigue loads on the turbine than with an upwind design

Turbine Classes

Four basic classes defined by the wind speed and turbulence data
The wind data is characterized by:

- the maximum wind speed to be expected as a mean value over 10 min, the so-called reference wind velocity ($v_{e\,ref}$)
- the mean annual wind speed ($\bar{v}_w$)
- the turbulence intensity at a wind speed of 15 m/s (I_{15})

Within the four classes, the two categories A and B characterize the design for different turbulence conditions:
The standard deviation (σ_1) of the longitudinal wind velocity (turbulence) is specified by the parameter *a*

Hau (2006), p. 180

Turbine Classes

WT Classes		I	II	III	IV	S
$v_{e\,ref}$	(m/s)	50	42.5	37.5	30	
$\bar{v}_w$	(m/s)	10	8.5	7.5	6.0	
$v_{G50} = 1.4v_{e\,ref}$		70	59.5	52.5	42	values to be
$v_{G1} = 1.05v_{G50}$		52.5	44.6	39.4	31.5	specified by
A	I_{15}	0.18	0.18	0.18	0.18	the designer
	a	2	2	2	2	
B	I_{15}	0.16	0.16	0.16	0.16	
	a	3	3	3	3	

IEC 61400-1 Hau (2006), p. 180

Turbine Classes

$v_{e\,ref}$ = the extreme wind speed averaged over 10 min

$\bar{v}_w$ = mean annual reference speed

v_{eG50} = 50 year gust

$$v_{eG50}(h) = 1.4v_{e\,ref} \cdot \left(\frac{h}{h_{hub}}\right)^{0.11}$$

v_{eG1} = annual gust (wind speed which is reached once per year)

$$v_{eG1}(h) = 0.75v_{eG50}(h)$$

Hau (2006), p. 182

Turbulence Intensity *I*

$$I_t = \frac{\sigma_t}{\bar{v}_t}$$

$$\sigma_t = \sqrt{\frac{1}{n-1}\sum_{i=t-n+1}^{t}(\mathrm{var}_i - \overline{\mathrm{var}})^2}$$

$$\bar{v}_t = \frac{1}{n}\sum_{i=t-n+1}^{t} v(i) \qquad \mathrm{var}_t = v(t) - \bar{v}_t$$

σ_t is the standard deviation of the wind speed variation about the mean wind speed $\bar{v}_t$ at time t

$\bar{v}_t$ is the mean wind speed over a certain interval at time t.

Blades

- ✓ Due to stability, modern wind turbines are designed with an odd number of rotor blades
- ✓ When the uppermost blade bends backwards while getting the maximum power from the wind, the lowermost blade passes into the wind shade in front of the tower

Blade Sizes

Examples:
TPI: Newton, IA (Impregnated TYCOR – sponge type material)
✓ 37m for GE 1.5MW turbine (manufactured)
✓ 48.7m for GE 2.5 MW turbine (to be manufactured)

Siemens: Ft Madison, IA (patented single piece casting of epoxy raisins)
✓ 45m for 2.5MW turbine
✓ 52m for 3.6MW turbine (sea-based applications, outside of US)

Blade Manufacturing

Basic manufacturing steps (TPI Corp):
✓ Infusion (reusable silicon bag technology)
✓ Demolding
✓ Assembly
✓ Inspection
✓ Transportation

Manufacturing challenge:
✓ Cost reduction

Energy challenge:
✓ Low energy manufacturing processes and optimized transport

Blade Transportation

Transportation cost
✓ Up to 25% of the blade cost

Blade packaging for transportation:
✓ Smaller blades, e.g., < 27 m (3 blades per truck)
✓ Medium size (2 blades per truck)
✓ Large blades (1 blade per truck)

Blade Sizes

Turbine power	Blade length
7MW blade	~75m
5MW blade	~65m
3.6MW blade	~55m
1.5MW blade	~40m
.75MW blade	~25m
.5MW blade	~20m
.1MW blade	~10m

Blade Design Challenge

Cost: Existing technology/expertise does not generally transfer

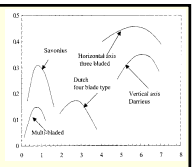
Example	High-end military applications	Aerospace applications	Wind-turbine blade
	~ $1,000/lb ~$10^6$ cycles	~ $100/lb ~$10^6$ cycles	~ $<10/lb ~$10^8$ cycles

Performance: Shape, materials, sensors (e.g., accelerometers) for active blade control
Weight: e.g., use of carbon fiber

Blade Design for Reliability

Design requirement: Failure probability p less than 10^{-5}

Number of Blades



Three-blade design concept
✓ Most popular

Two-blade design concept
✓ Lower cost and weight
✓ Higher rotational speed
✓ Hinged rotor that tilts to avoid heavy shocks to the turbine when a rotor blades passes the tower

Single-blade design concept
✓ A counterweight is required to balance the rotor

Turbine Noise

Sources of turbine noise:

✓Aerodynamic
Turbine rotor (blades) is the main source
✓Mechanical
Rotating parts, e.g., gears

Sources of Aerodynamic Noise

- ✓ Wind hitting an object generates a sound
- ✓ It may also set surfaces in vibration
- ✓ Turbine blades brake the wind to transfer its energy to the rotor thus emitting some white noise
- ✓ Sound pressure increases with the fifth power of the speed of the blade relative to the surrounding air
- ✓ Additive sound effect of multiple turbines

Design for Aerodynamic Noise

- ✓ Surfaces of the rotor blades must be smooth (Noise and aerodynamic reasons)
- ✓ Design of trailing edges key to sound reduction
- ✓ Different tip designs of blades (complex flow + largest speed)
- ✓ Low rotor speed
- ✓ Careful handling of rotor blades and maintenance

Design for Aerodynamic Noise

- ✓ Noise not a problem today
- ✓ Human perception versus reality
- ✓ The noise from the wind passing leaves, shrubs, trees, masts, etc. essentially masks sound from wind turbines operating at winds speeds around 4 - 7 m/s and up
- ✓ Sound maps

Design for Noise

Examples of sound levels

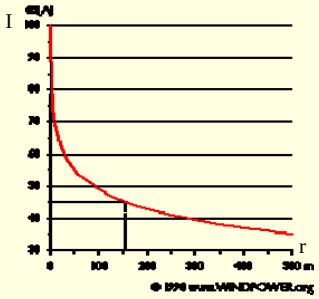
Sound Level	Threshold of Hearing	Whisper	Talking	City Traffic	Rock Concert	Jet Engine 10 m Away
dB [A]	0	30	60	90	120	150

A = absolute scale

http://en.wikipedia.org/wiki/Decibel

Design for Noise

Sound propagation and distance: Inverse square law



$I = P/4\pi r^2$

The noise level I in an inverse square of the distance r, where P = power at source

Design for Noise

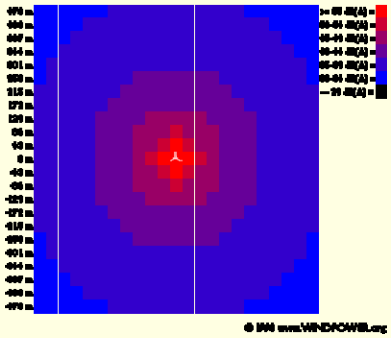
Example: Sound propagation and distance

- ✓ At one rotor diameter distance (e.g., 43 m) from the base of a wind turbine emitting 100 dB(A) the sound level is 55-60 dB(A)
- ✓ 4 rotor diameters (170 m) away the level is 44 dB(A),
- ✓ 6 rotor diameters (260 m) away the level is 40 dB(A).

Sound Level	Threshold of Hearing	Whisper	Talking	City Traffic	Rock Concert	Jet Engine 10 m Away
dB [A]	0	30	60	90	120	150

Design for Noise

Sound map



Sources of Mechanical Noise

- ✓ Metal components moving or knocking against each other generate noise (e.g., gearbox, drive train shaft, turbine generator

Gearbox Design for Noise

- ✓ Shift from industrial gearboxes to turbine specific gearboxes
- ✓ Steel wheels of the gearbox have a semi-soft, flexible core, and hard surface to ensure strength and long time wear
- ✓ Accomplished by heating gear wheels after the teeth have been ground, and then cooling them off slowly while they are packed in a special high carbon-content powder
- ✓ The carbon will then migrates into the surface of the metal
- ✓ This ensures a high carbon content and high durability in the surface of the metal, while the steel alloy in the interior remains softer and more flexible

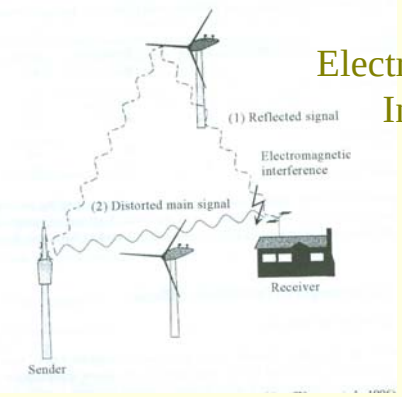
http://www.globalspec.com

Vibration Noise

Remedy

- ✓ Structural dynamics analysis to avoid vibration
- ✓ For example, holes drilled in a nacelle to avoid vibration
- ✓ Sound insulation rarely used today, although to reduce some medium- and high-frequency noise it could be applied

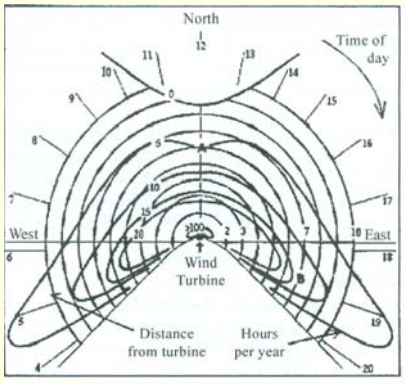
Turbine Electromagnetic Interference



- ✓ A concern to radar installations

J. F. Manwell *et al.* (2002), p, 493

Shadow Flicker and Flushing

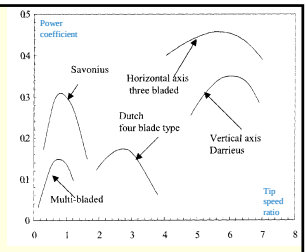


- ✓ Moving rotor may cast shadow or sunlight reflections may cause a flushing effect, both causing annoyance

J. F. Manwell *et al.* (2002), p, 508

Turbine Design Trade-offs

Photograph Soren Krohn © 1998 DWIA



Victoria in Southern Australia would never have been populated in the late 19th century, were it not for the water pumping windmills - and these windmills were actually optimized for the purpose they served

Turbine Design Trade-offs

Preamble

- ✓ An ideal wind turbine design is not dictated by technology alone, but by a tradeoff between technology and costs
- ✓ Turbine designs are optimized to deliver electricity at the lowest possible cost per kilowatt hour (kWh)
- ✓ The manufacturers are not very concerned with the efficiency of use the wind resource as the fuel is free
- ✓ Maximizing the annual energy production is not the primary design objective to avoid excessive costs of turbines

Generator vs Rotor Size

- ✓ A small generator, i.e., a generator with low rated power output in kW) requires less force to turn than a large one
- ✓ A large wind turbine rotor powering a small generator produces electricity for many hours of the year, however it captures only a small portion of the energy content of the wind at high speeds
- ✓ A large generator, on the other hand, is very efficient at high wind speeds, but unable to turn at low wind speeds

Acknowledgement

The material included in the presentation comes largely from the Danish Wind Industry Association