Wind Energy Systems

Lecture #4

Wind Energy and the Environment

- Wind turbines don't emit any pollution gas.
- Concerns include noise pollution, aesthetics, and bird collision.
- Wind is normally strongest at night when the power demand is the lowest.
- Small wind energy systems are very cost-effective to implement and can complement photovoltaic installations.

Wind Energy Evaluation

- Energy available in a wind stream is proportional to the cube of its speed.
- Wind resource is seldom a steady, consistent flow. It varies with the time of day, season, height above ground, and type of terrain.
- Typically annual average wind speeds of 5 meters per second (11 miles per hour) are required for grid-connected applications.
- Annual average wind speeds of 3 to 4 m/s (7-9 mph) may be adequate for non-connected electrical and mechanical applications such as battery charging and water pumping.
- Wind Power Density (watts per square meter) indicates how much energy is available at the site for conversion by a wind turbine.

Classes of Wind Power Density

Classes of Wind Power Density at 10 m and 50 m[(a)]

	10 m (33 ft)		50 m (164 ft)	
Wind Power Class	Wind Power Density (W/m^2)	Speed[(b)] m/s (mph)	Wind Power Density (W/m^2)	Speed[(b)] m/s (mph)
1	<100	<4.4 (9.8)	<200	<5.6 (12.5)
2	100 - 150	4.4 (9.8)/5.1 (11.5)	200 - 300	5.6 (12.5)/6.4 (14.3)
3	150 - 200	5.1 (11.5)/5.6 (12.5)	300 - 400	6.4 (14.3)/7.0 (15.7)
4	200 - 250	5.6 (12.5)/6.0 (13.4)	400 - 500	7.0 (15.7)/7.5 (16.8)
5	250 - 300	6.0 (13.4)/6.4 (14.3)	500 - 600	7.5 (16.8)/8.0 (17.9)
6	300 - 400	6.4 (14.3)/7.0 (15.7)	600 - 800	8.0 (17.9)/8.8 (19.7)
7	>400	>7.0 (15.7)	>800	>8.8 (19.7)

(a) Vertical extrapolation of wind speed based on the 1/7 power law

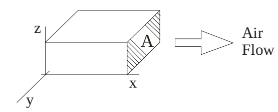
(b) Mean wind speed is based on the Rayleigh speed distribution of equivalent wind power density. Wind speed is for standard sea-level conditions. To maintain the same power density, speed increases 3%/1000 m (5%/5000 ft) of elevation. (from the Battelle Wind Energy Resource Atlas)

Estimation of the Wind Speed (Beaufort Table)

Degree	Classification	Effects of the wind on the nature	Speed (m/s)
0	calm	Everything is still. Smoke goes up vertically.	0.00-0.30
1	almost calm	Smoke is dispersed. Still weather vanes. The wind is felt on the face	0.30-1.40
2	breeze	Wind is felt on the face. It is heard the noise of leaves agitated by the wind. Weather vane moves.	1.40-3.00
3	fresh wind	Leaves and small branches of trees are constantly agitated. Flags are stretched out.	3.00-5.50
4	moderate wind	The wind lifts dust and paper from the ground. Small tree branches are agitated.	5.50-8.00
5	regular wind	Small trees with leaves begin to balance.	8.00-11.00
6	wind mildly strong	Large branches move, lines of electricity whistle. It begins to be difficult to walk against the wind.	11.00-14.00
7	strong wind	Whole trees are agitated. It is definitely difficult to walk against the wind.	14.00-17.00
8	very strong wind	Branches of trees break. It is necessary a great effort to walk.	17.00-21.00
9	windstorm	There is tile lifting.	21.00-25.00
10	gale	Trees are turn down. There are damages in constructions.	25.00-28.00
11	storm	The wind assumes characteristics of a hurricane, it rarely happens far away from coasts.	28.00-33.00
12	hurricane	The air is full of solid particles and drops of water. The sea is entirely whitish.	33.00-36.00

Theoretical Calculation of Wind Power

- A parcel of air moving along the horizontal axis:



- The kinetic energy is given by the following equation:

$$E_k = \frac{1}{2} m (V_W)^2 = \frac{1}{2} \rho A x (V_W)^2$$

where

A = cross sectional area of the air parcel moving in the x direction

ρ = air density

- The power in the wind (P_W) is the time derivative of the kinetic energy as:

$$P_w = \frac{d}{dt} E_k = \frac{1}{2} \delta A (V_W)^3$$

- A wind turbine modifies the local air speed and pressure. The speed of the air decreases as the turbine is approached causing the tube of air to enlarge to the turbine diameter. The air pressure rises to maximum just in front of the turbine and drops below atmospheric pressure behind the turbine.

- Considering v_1 the velocity before the turbine and v_2 the velocity after the turbine:

$$P_w = \frac{dE_k}{dt} = \frac{1}{4} \rho A (v_1^2 - v_2^2)(v_1 + v_2)$$

$$P_w = \frac{1}{4} \rho A v_1^3 \boxed{(1 - \frac{v_2^2}{v_1^2})(1 + \frac{v_2}{v_1})}$$

Betz Limit

- The power converted by the wind turbine can be given by the cube of the wind velocity multiplied by a coefficient C_p:

$$P_w = \frac{1}{2} \rho C_p A v_1^3$$

where C_p is defined as Betz Coefficient :

$$C_p = (1 - \frac{v_2^2}{v_1^2})(1 + \frac{v_2}{v_1}) / 2$$

which depends on the mechanical design of the turbine.

Betz Limit – Cont.

- If C_p is considered a function of v_1 and v_2, the maximum of such a function can be obtained for as (Betz limit):

$$\frac{v_2}{v_1} = \frac{1}{3}$$

$$C_p = 16/27 = 0.5926$$

for blades 100% efficient...

- In practice, the collection efficiency of a rotor is not as high as 59%, and a more typical efficiency is between 35% to 45%.

Power / Area Wind Energy

- An useful power / area equation can be used for estimation of energy potential, starting from :

$$P_t = (C_p \rho A V^3)/2$$

- The air density can be corrected by the gas law for every pressure and temperature of the place with the following expression:

$$\rho = 1.2929 \frac{273}{T} \frac{P}{760}$$

- At normal conditions T = 0 ºC and P = 760 mmHg the value of ρ is 1.192 kg/m³ and at T = 15 ºC (wind industry standard) and P = 760 and ρ is 1.225 kg/m³.

Power / Area Wind Energy – Cont.

- The air density can also be calculated in terms of the elevation of the wind above the sea level in meters

$$\rho = \frac{353}{T + 273} e^{\frac{-h}{29.3(T+273)}} \quad kg/m^3$$

- Substituting the Betz Limit for Cp and the air density at 15 ºC the following Power/Area is achieved :

$$P/A = 0.5926 \times 0.6464 \times V^3 = 0.3831 V^3$$

- Since Betz limit is too high, and there are other considerations to take into account such as aerodynamic losses in the rotor, wind speed variations in several points of the blade sweeping area, the rotor type, and so on.

Power / Area Wind Energy – Cont.

- Therefore, the following equation is a fair approximation for calculating the power density (W/m2) in a site with wind velocity V (in m/s) :

$$P/A = 0.25 V^3$$

- Another QND (quick and dirty) formula, as suggested by a few authors (where the velocity V_{mph} is in miles/hour):

$$P/A = 0.05472 V_{mph}^3$$

- Although those formulas are simple to use, they are valid for instantaneous power. For average power, there is a need to calculate the average of the cube of velocity.

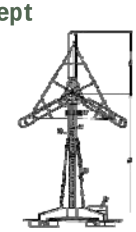
- There is no steady stream of wind... Therefore, statistical analysis must be performed.

Wind Energy Technologies

- **Horizontal Axis Turbines (HAWT)**
  Horizontal axis turbines are the most common turbine configuration used today. They consist of a tall tower, atop which sits a fan-like rotor that faces into or away from the wind, the generator, the controller, and other components. Most horizontal axis turbines built today are two- or three-bladed, although some have fewer or more blades.

- **Vertical Axis Turbines (VAWT)**
  Vertical axis turbines fall into two major categories: Savonius and Darrieus. Neither turbine type is in wide use today.
  - Savonius Turbines
    First invented in Finland, the Savonius turbine is S-shaped if viewed from above. This drag-type VAWT turns relatively slowly, but yields a high torque. It is useful for grinding grain, pumping water, and many other tasks, but its slow rotational speeds are not good for generating electricity.
  - Darrieus Turbines
    The Darrieus turbine was invented in France in the 1920s. Often described as looking like an eggbeater, this vertical axis turbine has vertical blades that rotate into and out of the wind. Using aerodynamic lift, these turbines can capture more energy than drag devices. The Giromill and cycloturbine are variants on the Darrieus turbine.

The Danish Three-Bladed Concept



- **Most modern wind turbines are three-bladed designs with the rotor position maintained upwind (on the windy side of the tower) using electrical motors in their yaw mechanism.**
- **This design is usually called the classical Danish concept , and tends to be a standard against which other concepts are evaluated. The vast majority of the turbines sold in world markets have this design.**
- **The basic design was first introduced with the renowned Gedser (see picture) wind turbine. Another characteristic is the use of an asynchronous generator.**

Two-Bladed (Teetering) Concept

- **Two-bladed wind turbine designs have the advantage of saving the cost of one rotor blade and its weight. However, they tend to have difficulty in penetrating the market, partly because they require higher rotational speed to yield the same energy output. This is a disadvantage both in regard to noise and visual intrusion. Lately, several traditional manufacturers of two-bladed machines have switched to three-bladed designs.**
- **The rotor has to be able to tilt in order to avoid too heavy shocks to the turbine when a rotor blades passes the tower. The rotor is therefore fitted onto a shaft which is perpendicular to the main shaft, and which rotates along with the main shaft. This arrangement may require additional shock absorbers to prevent the rotor blade from hitting the tower.**

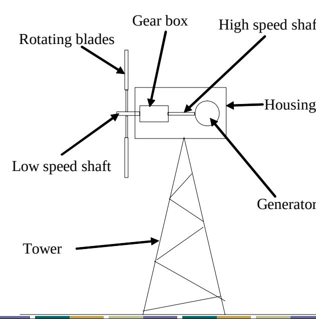
Typical Wind Turbines

Vertical Axis Wind Turbine

Wind Farm

Off-Shore Wind Energy System

Wind Turbine Electromechanical System



Home

Turbine Efficiency

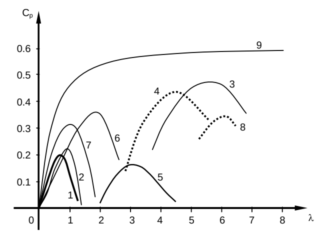
Input power from Wind → Losses in rotating blades and rotor mechanism

Input to gearbox → Losses in gearbox

Input to generator → Losses in generator

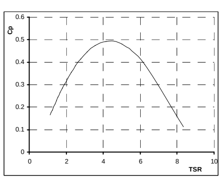
Output power

Power Curve Depends on Turbine Type



1 - Savonius
2 - Filippini turbine
3 - rotor with 2 blades, HAWT
4 - rotor with 3 blades
5 - rotor with 4 blades (type Dutch Mill)
6 - rotor with 6 blades
7 - rotor with multiple blades, of farm or spiked
8 – Darrieus turbine
9 - Theoretical turbine

Peak Power Occurs at a Particular TSR

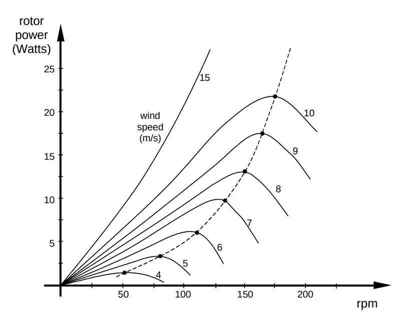


$$TSR = \frac{v_{tip}}{v}$$

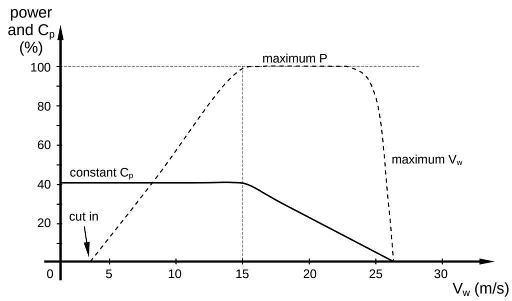
$$v_{tip} = \omega\, r = 2\pi\, n\, r$$

- **The tip velocity of the turbine is less than wind speed.**
  - *v:* wind speed
  - v_{tip}: tip velocity of blade
  - *n:* rotor speed of generator
- **TSR can be changed by changing the pitch angle**

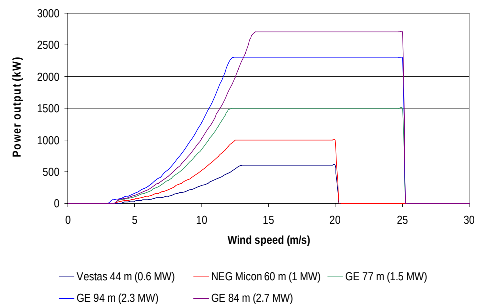
Wind Power Curve Tracking



Speed Control Range



Use of Power Output Curve to Compare Turbines



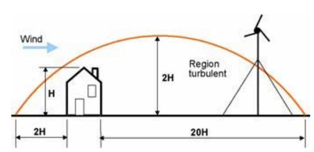
Anemometer Data Supports Site Evaluation

Impact of Tower Height

$$\left(\frac{v}{v_o}\right) = \left(\frac{H}{H_o}\right)^{\alpha}$$

- **Most used**

$$\left(\frac{v}{v_o}\right) = \frac{\ln(H/z)}{\ln(H_o/z)}$$



Friction Coefficient for Various Terrain Characteristics

Friction Coefficient for Various Terrain Characteristics

Terrain Characteristics	Friction Coefficient α
Smooth hard ground, calm water	0.10
Tal grass on level ground	0.15
High crops, hedges and shrubs	0.20
Wooded contryside, many trees	0.25
Small town with trees and shrubs	0.30
Large city with tall buildings	0.40

Roughness Classification

Roughness Classification

Roughness Class	Description	Roughness Length z(m)
0	Water surface	0.0002
1	Open surface with a few windbreaks	0.03
2	Farm land with windbreaks more than 1 km apart	0.1
3	Urban districts and farm land with many windbreaks	0.4
4	Dense urban area or forest	1.60

Correction for Height Measurements

- **If you have anemometer data from a 10-m tower (6 m/s ave.) across a surface of crops, hedges, and shrubs and want to estimate how much higher the wind is at 40 meters, how do you do it?**

  SOLUTION

$$\left(\frac{v}{v_o = 6m/s}\right) = \left(\frac{H = 40m}{H_o = 10m}\right)^{\alpha = 0.2}$$

$$\left(\frac{v}{v_o = 6m/s}\right) = 1.32 \therefore v = 7.92m/s$$

Statistical Analysis

- **Since wind is variable and average power is proportional to the average of the cubic of wind speed, we need some formulas for calculation of wind speed, root mean cubic power and energy density over a number of speed samples during the year. We can assume** $\rho_i = 1.225kg/m^3$ **at** $t = 15^{\circ}C$.

average speed	root mean cubic speed	cubic power density	cubic energy density
$V_{av} = \frac{1}{n}\sum_{i=1}^{n} v_i$	$V_{rmc} = \sqrt[3]{\frac{1}{n}\sum_{i=1}^{n} v_i^3}$	$P_{rmc} = \frac{1}{2n}\sum_{i=1}^{n} \rho_i v_i^3$	$E_{yw} = \frac{8{,}760}{2n}\sum_{i=1}^{n} \rho_i v_i^3$
m/s	m/s	W/m^2	$Wh/m^2/y$

Power in terms of Height

- Given that wind power is proportional to the average of cubic power, calculate the the correction factor in terms of height, for power.

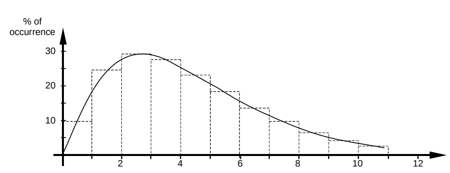
$$\left(\frac{P}{P_0}\right)=\left(\frac{\frac{1}{2}\rho A v^3}{\frac{1}{2}\rho A v_o^3}\right)=\left(\frac{v}{v_o}\right)^3=\left(\frac{H}{H_0}\right)^{3\alpha}$$

Rotor Stress

- A wind turbine with a 30-m rotor diameter is mounted with its hub a 50 m above a ground surface that is characterized by shrubs and hedges. Estimate the ratio of specific power in the wind at the highest point that a rotor blade tip reaches to the lowest point that it falls to.

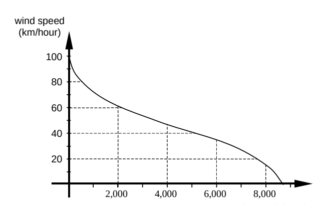
Wind Speed Distribution

- The figure displays a typical curve of wind speed distribution for a given site. That distribution can be made monthly or annually. It is determined through bars of occurrence numbers, or percentile of occurrence, for each range of wind speed during a long period of time.



Annual Wind Speed Distribution

- In order to establish a probability distribution, it is important to establish the duration curve of the wind speed for every hour of the day, every day of the year, in a total of 8,760 data. The figure shows a curve formed by points marked in several ranges of speed, in accordance to the accumulated number of hours of a particular wind intensity and above that range



Weibull Probability Function

- Random nature of the wind:

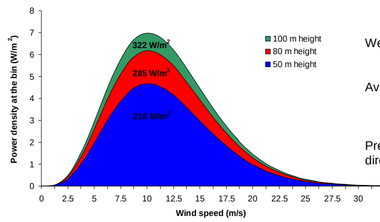
$$h(v) = (\frac{k}{c})(\frac{v}{c})^{k-1} e^{-(v/c)^k} \qquad 0 < v < \infty$$

- When k = 2 this function is known as the Rayleigh function (typical universal probalistic distribution):

$$h(v) = (\frac{2}{c})(\frac{v}{c}) e^{-(v/c)^2}$$

- "c" is known as the scale factor and "k" is the shape factor.

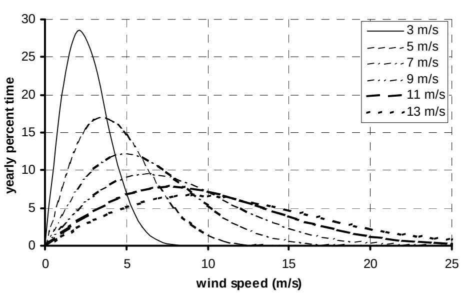
Weibull Distribution of Wind Speed



Weibull parameters	Shape, k = 1.40 Scale, c = 5.35
Average speed	50 m, v = 4.9 m/s 80 m, v = 5.4 m/s 100 m, v = 5.6 m/s
Prevailing wind direction	209 deg SW

Rayleigh Distribution of the Wind Speed

The area calculated between two wind velocities, v_1 and v_2 is the probability that the wind is between v_1 and v_2.



Raylegh Power Density Assumptions

- For the Raylegh power density function

$$f(v) = \frac{2v}{c^2} \exp\left[-\left(\frac{v}{c}\right)^2\right]$$

- We can calculate the average cubic velocity as :

$$(v^3)_{avg} = \int_0^\infty v^3 \cdot f(v) dv = \int_0^\infty v^3 \cdot \frac{2v}{c^2} \exp\left[-\left(\frac{v}{c}\right)^2\right] dv = \frac{3}{4} c^3 \sqrt{\pi}$$

- There is a direct relationship between scaling factor and average wind speed:

$$v_{avg} = \int_0^\infty v \cdot f(v) dv = \frac{\sqrt{\pi}}{2} c \approx 0.886c$$

Raylegh Power Density Assumptions – Cont.

- Then

$$c = \frac{2}{\sqrt{\pi}} v_{avg}$$

- Substituting back in the average of the cubic wind

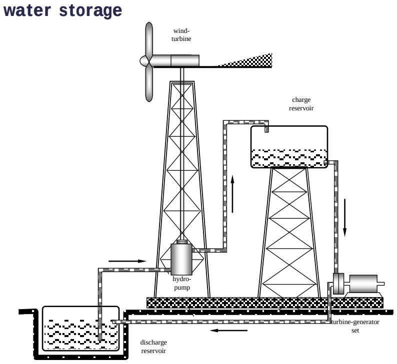
$$\left(v^3\right)_{avg} = \frac{3}{4}\left(\frac{2}{\sqrt{\pi}} v_{avg}\right)^3 \sqrt{\pi} \approx 1.91\left(v_{avg}\right)^3$$

- Therefore, under Raylegh wind assumptions, the average power can be calculated as:

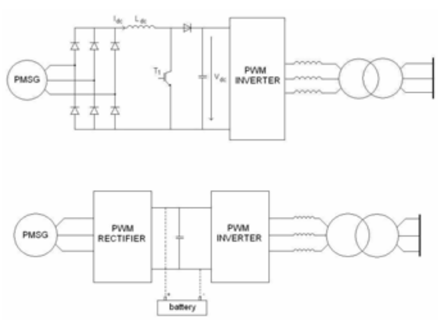
$$P_{avg} = \frac{6}{\pi} \cdot \frac{1}{2} \cdot \rho \cdot A \cdot \left(v_{avg}\right)^3 \qquad P_{avg}/A = \frac{6}{\pi} \cdot \frac{1}{2} \cdot \rho \cdot \left(v_{avg}\right)^3 \quad W/m^2$$

Wind Variation Must Be Compensated by Storage

Example: water storage

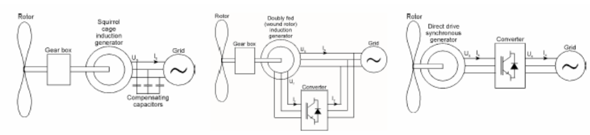


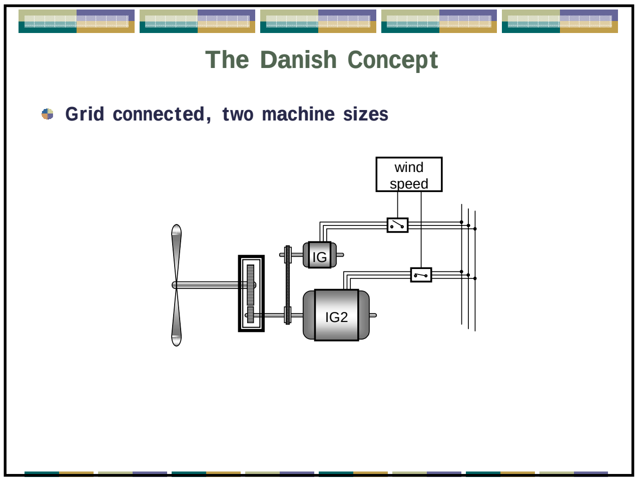
PM Generators for Wind Systems



Induction Generator

- Grid Connected
- Doubly Fed, Rotor Converter
- Front End Converter




The Danish Concept
Grid connected, two machine sizes
wind speed
IG
IG2


Questions ?