Wind as Fuel

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Measuring Wind Speed

Wind speed: Anemometer types

- ✓ Cup anemometer
- ✓ Propeller anemometer
- ✓ Pressure plate anemometer
- ✓ Pressure tube anemometer
- ✓ Sonic anemometer

Wind direction: Vanes

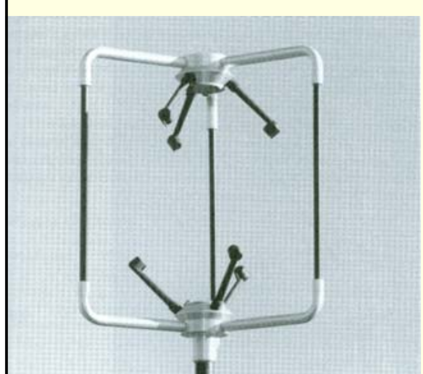
Measuring Wind Speed

Anemometer

http://www.nrel.gov/wind/%20wind_pubs.htm

www.secondwind.com

Measuring Wind Speed



Ultrasonic anemometer

E. Hau (2006), p. 475

Self-powered, Wireless Anemometer

- ✓ Anemometer provides its own power from a self-contained generator
- ✓ Wireless transmission of data back to a base station up to 300 feet away, eliminating the need for wires, batteries, or solar panels

http://www.etesian-tech.com

Self-powered, Wireless Anemometer

Transmitter

Receiver

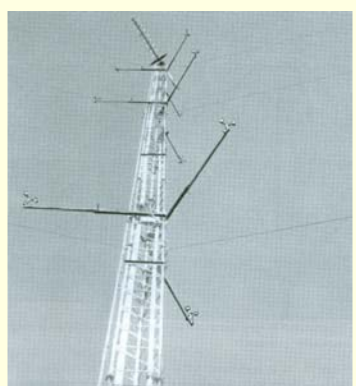
Power supply for receiver

Antenna (optional)

http://www.etesian-tech.com

SODAR

www.secondwind.com



Met Tower

E. Hau (2006), p. 476

The Power of the Wind

Power of the wind

$$P = 0.5 \times \rho \times A \times v^3$$

P = power [W]
ρ = air density [kg/m^3]
A = rotor swept area [m^2]
v = wind speed [m/s]

Unit Converter
http://www.denysschen.com/catalogue/unitsConverter.aspx

The Power of the Wind

Example

Assumptions:
Air temperature (see level) = 15 C
Air density = 1.225 kg/m^3

Wind Speed [m/s]	Power/Area [W/m2]
0	0
5	80
10	610
15	2,070
20	4,900
25	9,560
30	16,550

The Power of the Wind

Evaluation of the wind resource → Wind resource map

Simple method

Average P/A < 100W/m^2 ⇨ Poor wind resource

Average P/A ~ 400W/m^2 ⇨ Good wind resource

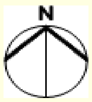
Average P/A > 700W/m^2 ⇨ Great wind resource

P/A = Power over Area

Wind Speed [m/s]	Power/Area [W/m2]
0	0
5	80
10	610
15	2,070
20	4,900
25	9,560
30	16,550

Wind Resource

- ✓ Global patterns
- ✓ Atmospheric circulation patters



Wind: Global Origin

- ✓ Uneven heating of the earth by solar radiation leads to pressure differences across earth's surface
- ✓ Air circulation due to uneven earth heating is distorted by the earth circulation and uneven speeds (~ 600km/h at the Equator, and 0 at the Pole)

Assumption: Smooth spherical surface

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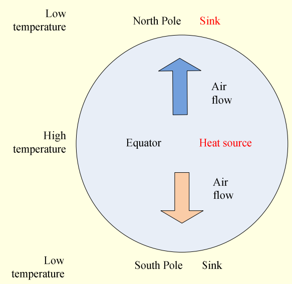
Wind: Global Origin

Temperature differences



Simplified (abstract) air flow model

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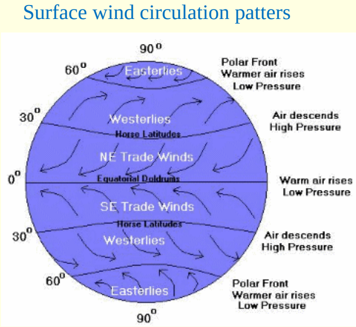
Wind: Global Origin

Surface wind circulation patters



- ✓ The equator receives the Sun's direct rays. Here, air is heated and rises, leaving low pressure areas behind
- ✓ Moving to about 30 deg. North and South of the equator, the warm air from the equator begins to cool and sink
- ✓ Between 30 deg. latitude and the Equator, most of the cooling sinking air moves back to the equator. The rest of the air flows toward the poles

http://www.weatherwizkids.com/wind1.htm

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Wind: Definitions

- ✓ Trade winds: Air movements toward the equator. The Coriolis effect makes the trade winds appear to be curving to the west.
- ✓ Doldrums: The trade winds coming from the south and the north to meet near the equator converge and produce upward winds as they are heated
- ✓ Prevailing westerlies: Between 30 and 60 deg. latitude, the winds that move toward the poles appear to curve to the east As winds are named from the direction in which they originate, these winds are called prevailing westerlies
- ✓ Polar easterlies: At about 60 deg. latitude in both hemispheres, the prevailing westerlies join with the polar easterlies to reduce upward motion

http://en.wikipedia.org/wiki/**Coriolis_effect**

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Wind: Atmospheric Circulation Patterns

Assumption: Smooth spherical surface

- ✓ Mountains
- ✓ Oceans (acting as energy sinks)
- ✓ Local heating and cooling

Secondary and tertiary air circulation

Wind: Atmospheric Circulation Patterns

Secondary air circulation (heating and cooling of the lower atmosphere):

- ✓ Hurricanes
- ✓ Monsoons
- ✓ Extra-tropical cyclones

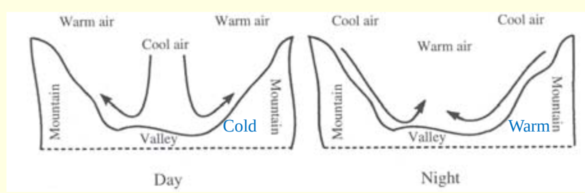
Wind: Atmospheric Circulation Patterns

Tertiary air circulation (local):

- ✓ Land and see breezes
- ✓ Valley and mountain winds
- ✓ Monsoon like flow (e.g., Flow in California passes)
- ✓ Foehn winds (Dry high-temperature winds in mountain ranges)
- ✓ Thunderstorms
- ✓ Tornadoes

Wind: Atmospheric Circulation Patterns

Example of tertiary circulation: Valley and mountains winds



Rohati and Nelson (1994)

General Wind Characteristics

- Inter-annual
- Annual
- Diurnal
- Short term

Time scales:

✓ Inter-annual (> a year)
[min 30 years of data to determine long term values]
✓ Annual
[min 5 years of data to determine annual average]
✓ Diurnal (time of day)
✓ Short term

General Wind Characteristics

- Inter-annual
- Annual
- Diurnal
- Short term

Inter-annual (> a year)

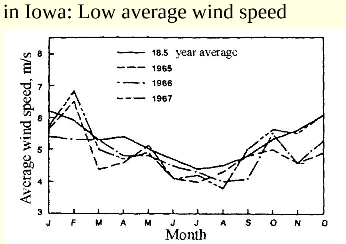
Rule: A year worth of data record is generally sufficient to predict seasonal mean wind speeds with 10% error at confidence level of 90%

General Wind Characteristics

Annual

Seasonal and monthly variations in wind speed, e.g.,
January in Iowa: High average wind speed
July in Iowa: Low average wind speed

- Inter-annual
- Annual
- Diurnal
- Short term



Seasonal changes of monthly average wind speeds (Hiester and Pennell 1981)

General Wind Characteristics

- Inter-annual
- Annual
- Diurnal
- Short term

Diurnal

Differential heating of the earth during the day and night leads to:

✓ Higher average wind speed during the day

✓ Lower average wind speed during the hours between midnight and sunrise

General Wind Characteristics

- ✓ Inter-annual
- ✓ Annual
- ✓ Diurnal
- ✓ Short term

Short-term

- ✓ Short-term usually implies variations over time intervals 10 min or less
- ✓ Short-term wind speed variations are usually due to turbulence and gusts

Turbulence = Random wind speed fluctuation
Gust = Discrete event within a turbulent wind field

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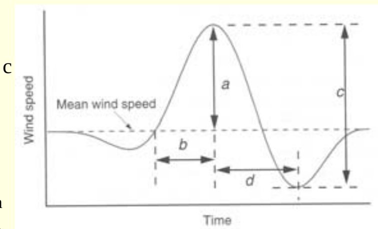
General Wind Characteristics

Gust characterization

- ✓ Amplitude – a
- ✓ Raise time – b
- ✓ Max gust variation – c
- ✓ Lapse time – d



Gust = Discrete event within a turbulent wind field

Manwell *et al.* (2002)

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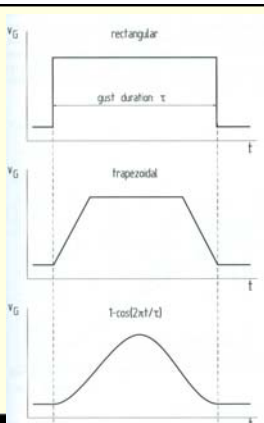

Idealized Gust Shapes

Hau (2006), p. 175

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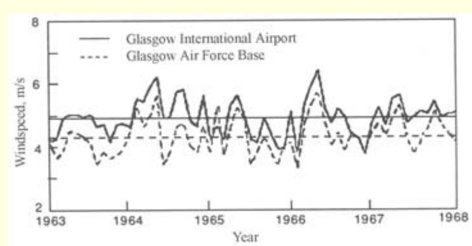
General Wind Characteristics

Wind speeds at different locations



Hiester and Pennell (1981)

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General Wind Characteristics

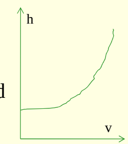
Wind direction

- ✓ Wind direction varies in the same scale as wind speed - e.g., minutes to years
- ✓ Seasonal variations may be small, e.g., 30 degrees
- ✓ Wind direction may change by 180 degrees over a year period

- Horizontal axis turbines rotate yaw with changes in the wind direction
- Short term changes in wind direction increases a load on blades and a yaw mechanism thus accelerating their fatigue

Atmospheric Boundary Layer

Characteristics:



- ✓ (Horizontal) wind speed varies with height
- ✓ The variation of wind speed with elevation is called a vertical wind shear or vertical wind speed profile

Of particular interest to wind energy:

- ✓ Short scale (seconds) variation of wind speed with height (wind shear)
- ✓ Seasonal variation of wind speed with height

Atmospheric Boundary Layer

$$\text{Lapse rate} = \frac{\Delta\ \text{Temperature}}{\Delta\ \text{Height}}$$

Assumption:
Sea level temperature = 288 K
Temp at 10,800 m = 216.6 K

$\Delta T/\Delta z$ = (216.6 – 288) [K]/10,800 [m] = - 0.0066 [C/m] = - 0.00357 [F/ft]

Unit Converter
http://www.denysschen.com/catalogue/unitsConverter.aspx

Atmospheric Boundary Layer

Air density ρ

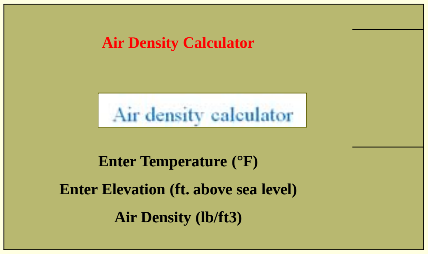
Assumption
Air = Ideal gas

$$\rho = 3.4837\ p/T$$

ρ = air density [kg/m^3]
p = air pressure [kN/m^2]
T = air temperature [Kelvin]

$$P = 0.5 \times \rho \times A \times v^3$$

Air Density Calculator



http://www.denysschen.com/catalogue/density.asp

Atmospheric Boundary Layer

Assumptions
Sea-level temperature = 288.15 [K] (15C, 59F)
Sea-level pressure = 101.325 [kN/m^2] (14.696 psi)
Sea-level air density 1.225 [kg/m^3]
Limited to the elevation up to 5,000 [m]

Atmospheric pressure:

$$p = 101.29 - (0.011837)z + (4.793 * 10^{-7})z^2$$

p = pressure [kN/m^2]
z = elevation [m]

$\rho = 3.4837\ p/T$ ⇨ $P = 0.5 \times \rho \times A \times v^3$

Atmospheric Boundary Layer

Turbulence in the wind is caused by dissipation of wind’s kinetic energy into thermal energy via the creation and destruction of progressively smaller eddies (or gusts)

Turbulent wind over a short time (min or less) may be highly variable while over longer horizons (hour or longer) may have relatively stable mean speed

Atmospheric Boundary Layer

Turbulence metrics

- ✓ Turbulence intensity

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

σ_t the standard deviation of the wind speed variation at time t
$\bar{v}_t$ the mean wind speed over a certain interval at time t

- ✓ Wind speed probability density function
- ✓ Autocorrelation
- ✓ Integral time scale/length scale
- ✓ Power spectral density function

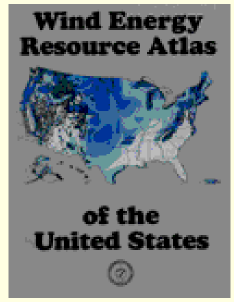
Wind Forecasting

Forecasting horizon:
✓ Long, e.g., 24h +
✓ Short, e.g., minutes to 1h +

http://www.garradhassan.com/services/ghforecaster/accuracy.php

Power prediction (forecasting) vs wind forecasting

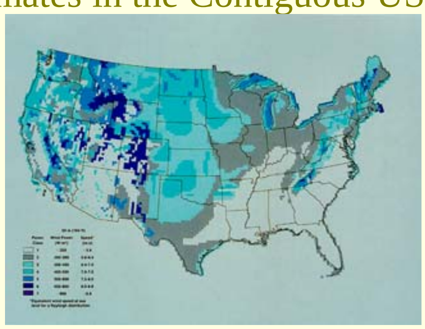
Wind Energy Resource Atlas of the United States



http://rredc.nrel.gov/wind/pubs/atlas/atlas_index.html

Annual Average Wind Resource Estimates in the Contiguous US

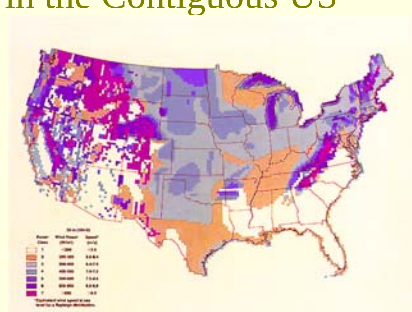
Example Map:
US Atlas



http://rredc.nrel.gov/wind/pubs/atlas/maps/chap2/2-06m.html

Winter Wind Resource Estimates in the Contiguous US

Example Map:
US Atlas



http://rredc.nrel.gov/wind/pubs/atlas/maps/chap2/2-12m.html

Acknowledgement

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