WIND POWER

Agenda

Resources and Utilization

Reading Assignments

- Global & local wind resources/patterns

Technology

- Wind tower design and functionality
  - Wind speed distributions
  - Turbine power generation, design parameters
  - Blade aerodynamics, lift and drag, wake turbulence
- Wind farms, design and operations
  - Onshore and offshore windfarms, useful life
  - Construction parameters, cost, GHG emissions

- Strategic issues
  - Performance
  - Ecological impact, wildlife habitat

Wind power in national and international energy mix

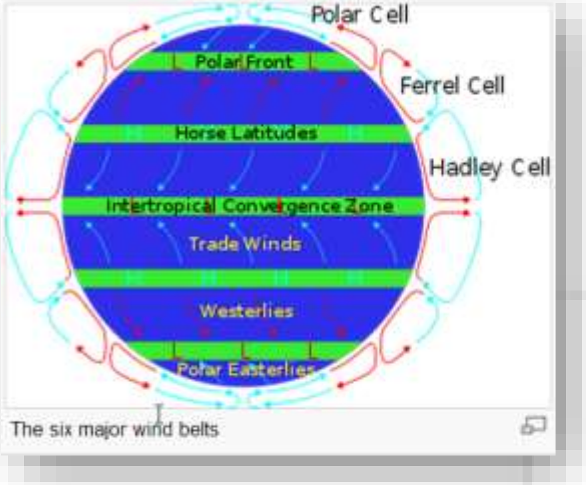
First US Wind Farms

Altamont Pass (CA), started around 1980 >1,000 towers, 0.5 GW, many inoperable after 1982

To protect birds in the Altamont Pass, ½ of all turbines are shut down during November-December, the other ½ during January-February.

Entire project has been rebuilt with newer turbines.

Global Wind Patterns

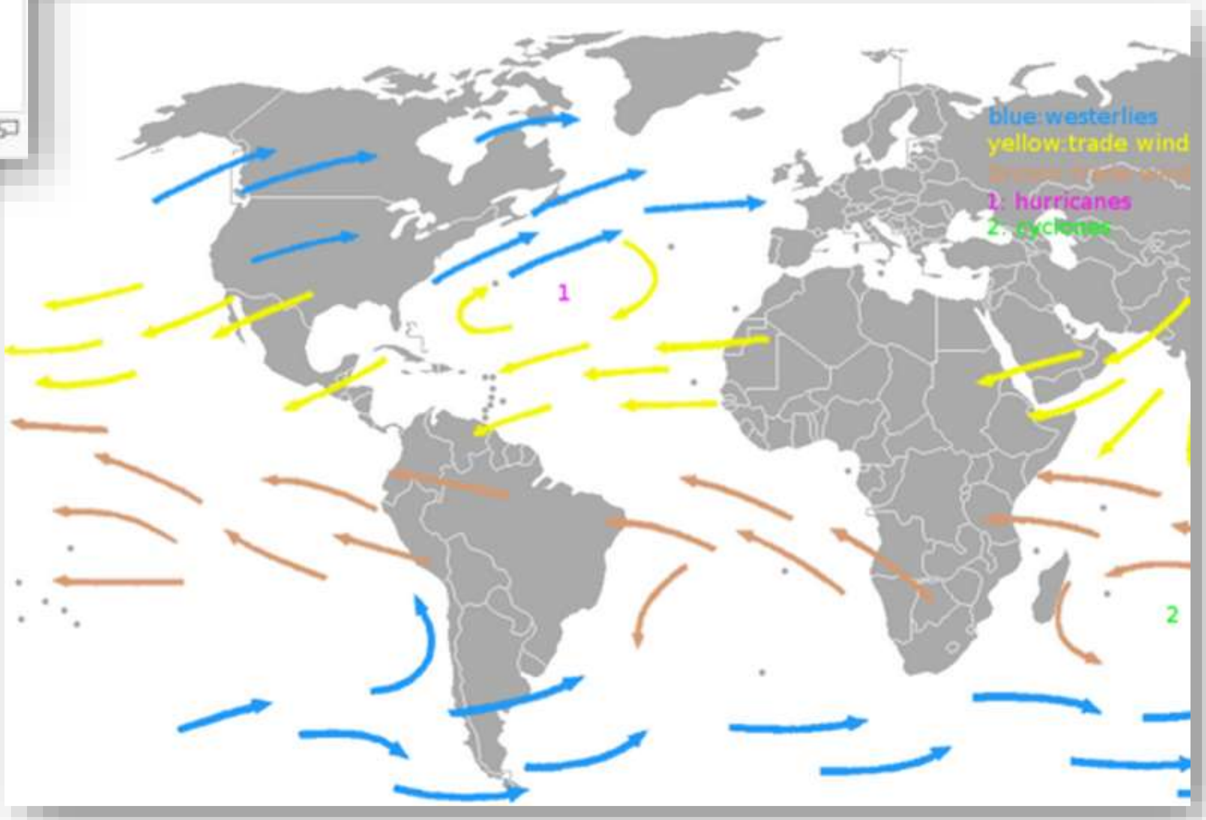


The six major wind belts

Latitudinal variation of solar insolation → Equator updraft upper air flow in pole directions are destabilized by **Coriolis** force (→ deviation to East on both hemispheres) → Pattern breaks up into 3 regions (cells) per hemisphere.

Westerlies and NE trade winds near 30^0 latitudes. High-altitude jet stream (v > 300 km/h)

Regional and local wind patterns are influenced by terrain features (friction, uplifts and downdrafts), thermal gradients, bodies of water, movement and interactions of large air masses.



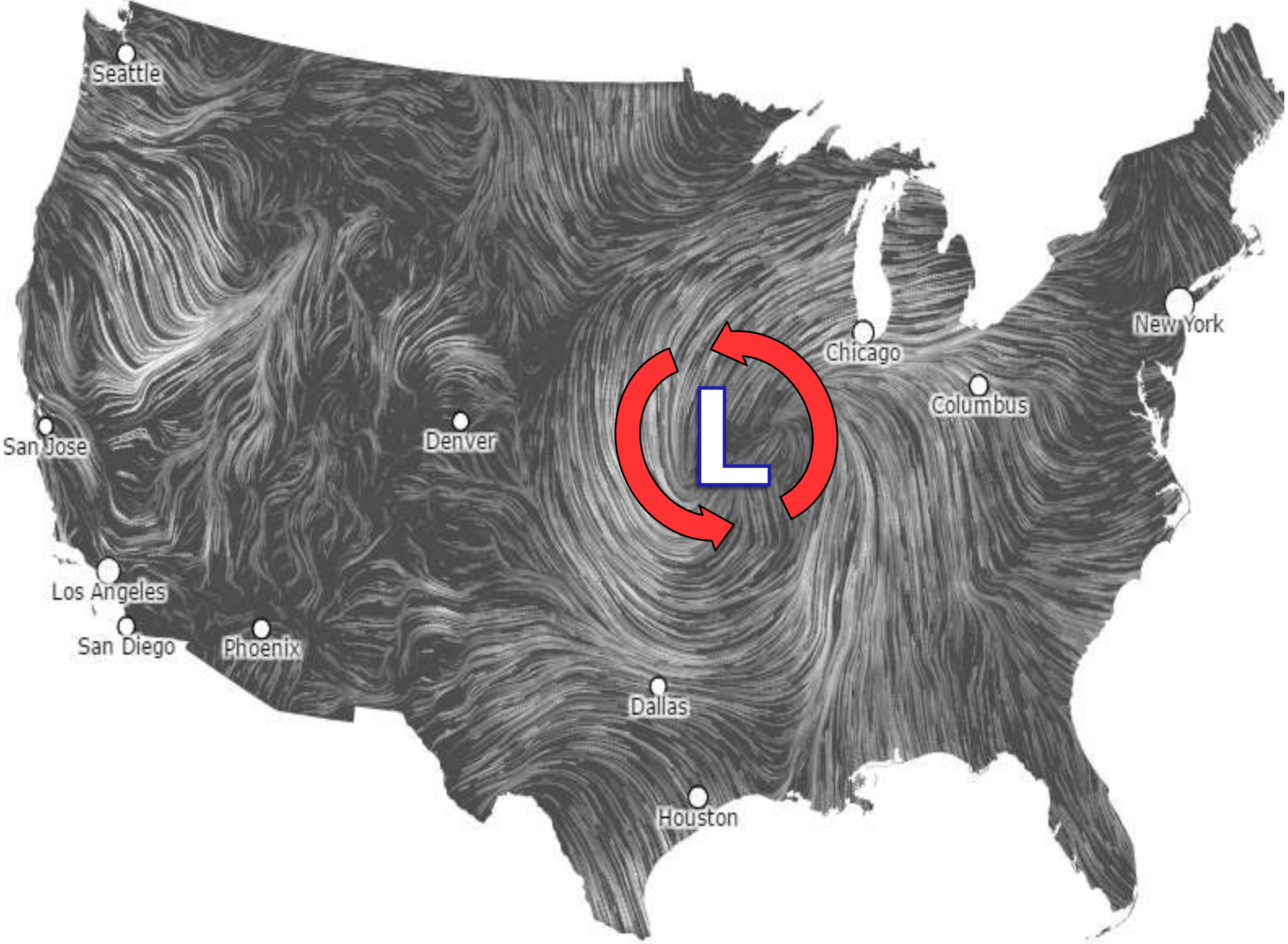
ROC 43.16^0 N, 77.61^0 W

US Instant Wind Patterns

March 30, 2017
10:35 am EST
(time of forecast download)

top speed: **33.7 mph**
average: **9.7 mph**

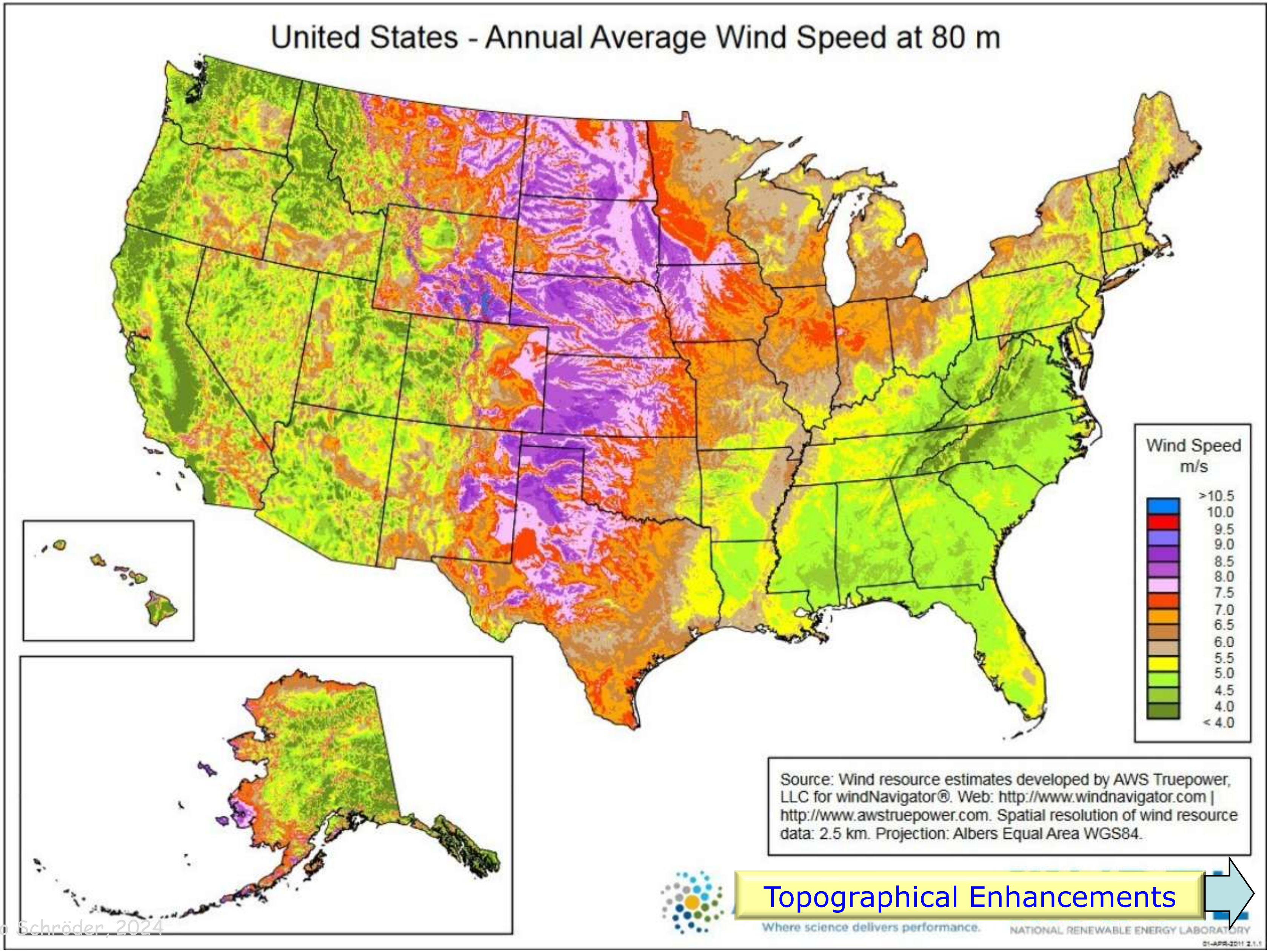
Anticyclone storm in Mid West, calm at east coast



Windpattern animation

http://hint.fm/wind/index.html

US Wind Resources Potential

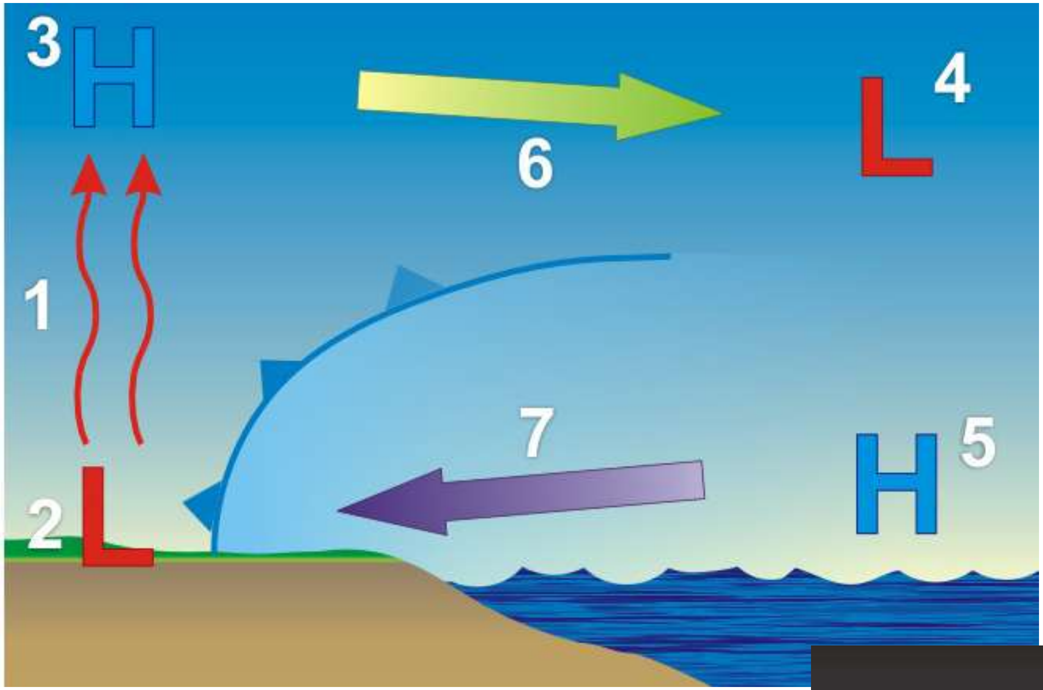


United States - Annual Average Wind Speed at 80 m

Source: Wind resource estimates developed by AWS Truepower, LLC for windNavigator®. Web: http://www.windnavigator.com | http://www.awstruepower.com. Spatial resolution of wind resource data: 2.5 km. Projection: Albers Equal Area WGS84.

Topographical Enhancements

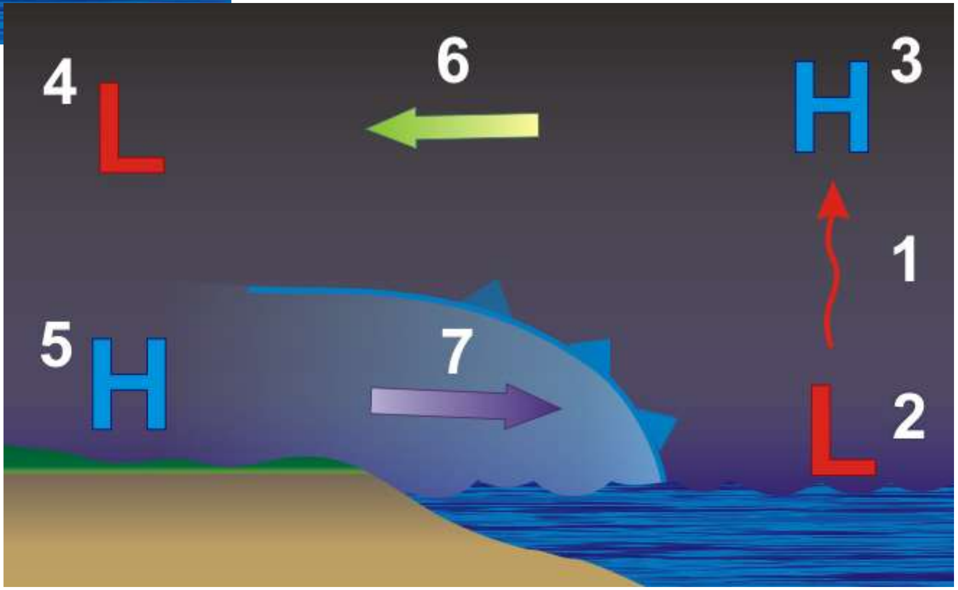
Sea Breeze-Land Breeze



Heat capacity (thermal inertia) of water is higher than heat capacity of land.

Due to thermal convection, air over warmer part ascends 1, creates low-pressure region L 2, filled in by airflow 7 from high H 5 over colder water.

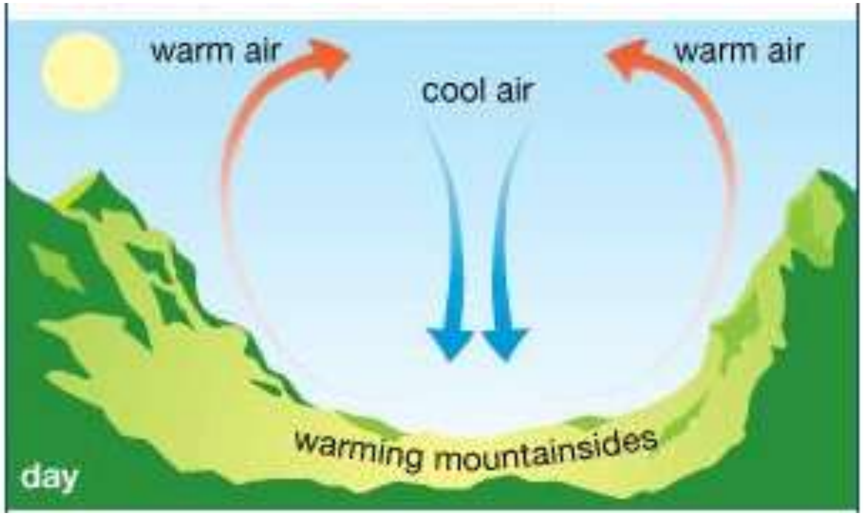
Day-time: Sea breeze 7
Return flow 6.

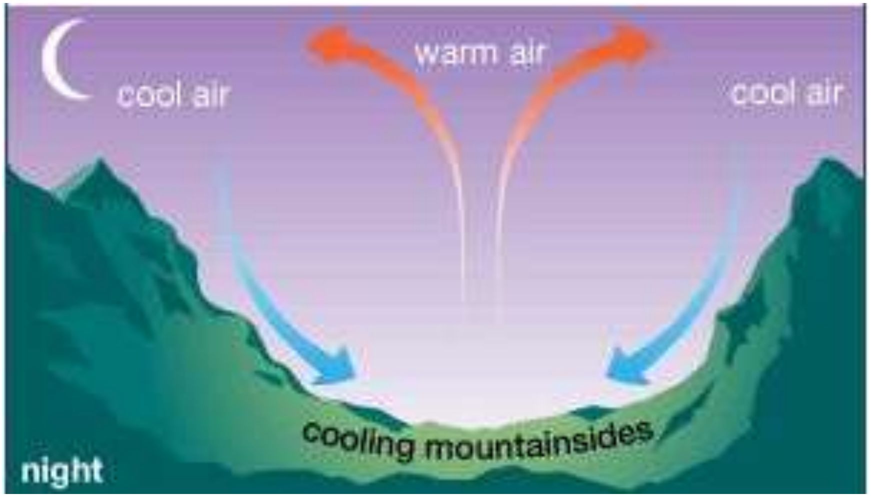


Radiation cooling of land during night depletes heat content of land faster than of body of water (lake, ocean), producing high-pressure domain 5 on land, low L 2 over water.

Night-time: Land breeze 7
Return flow 6.

Valley and Mountain Breezes





Art. *Encyclopædia Britannica Online*. Web. 7 Mar. 2013. <http://www.britannica.com/EBchecked/media/111214/When-the-valley-floor-warms-during-the-day-warm-air>.

When the mountain slopes warm during the day, warm air rises up the slopes of surrounding mountains and hills to create a valley breeze.

At night, denser cool air slides down the slopes to settle in the valley, producing a mountain breeze.

Similarly: Mountain passes, ridges, spires can channel winds.

Environmental concerns: Birds use these wind patterns efficiently.

Agenda

Resources and Utilization

Reading Assignments

- Global & local wind resources/patterns

Technology

- Wind tower design and functionality
  - Wind speed distributions
  - Turbine power generation, design parameters
  - Blade aerodynamics, lift and drag, wake turbulence
- Wind farms, design and operations
  - Onshore and offshore windfarms, useful life
  - Construction parameters, cost, GHG emissions

- Strategic issues
  - Performance
  - Ecological impact, wildlife habitat

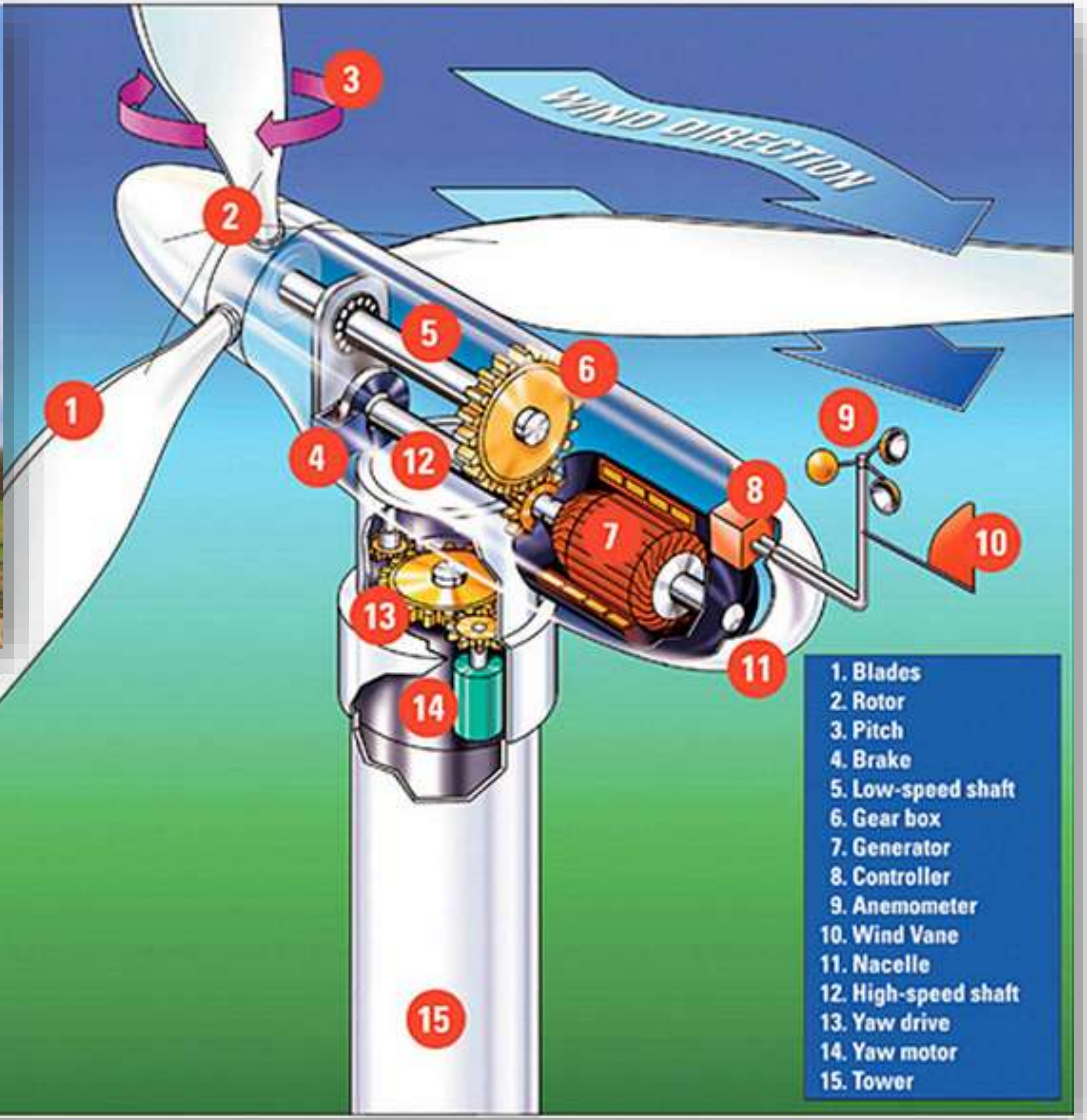
Wind power in national and international energy mix

Basic Wind Tower Construction

17th-century windmill (Northern Germany).

Manual yaw control of nacelle and pitch control of rotors (sails).

Modern rotor blades are aerodynamically optimized (“airfoils”).

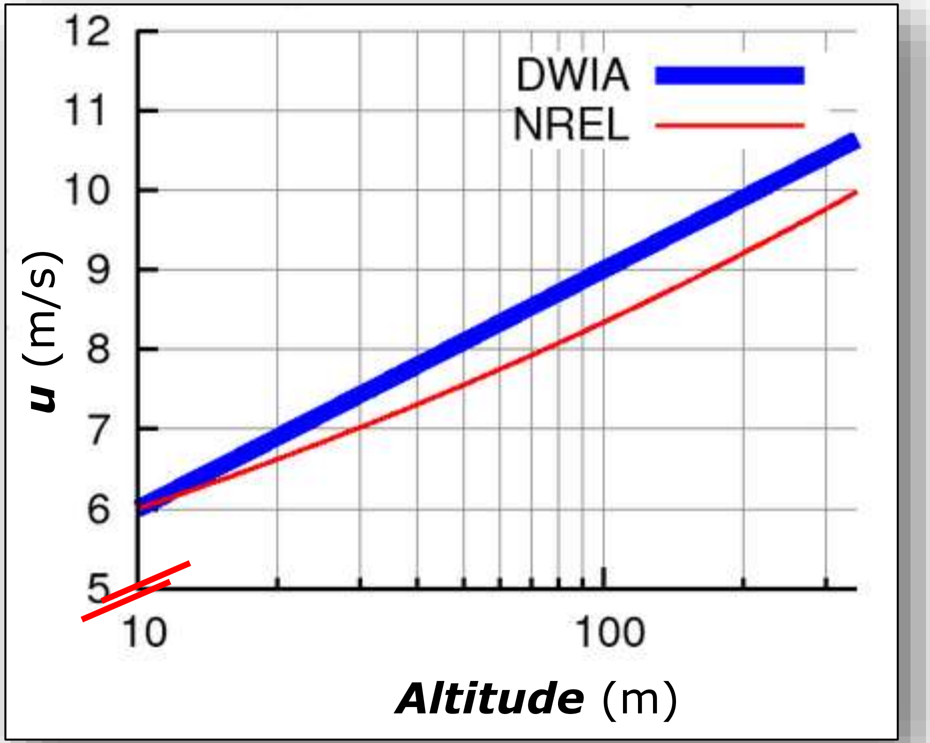


Offshore Giant Wind Towers

Alpha Ventus Windfarm 60MW
$ 325 M ($5.42/W)
EWE 47.5%; E.ON and Vattenfall each 26.25%

Zukunftstechnologie Windturbine: Viele kühne Sprünge Foto: Witthaya Prasongsin / Getty Images

Altitude Dependence of Mean Wind Speed



Close to ground level, uneven landscape (buildings, trees, power lines) produces friction & turbulent wind patterns (wind shear) = obstacles to laminar flow.

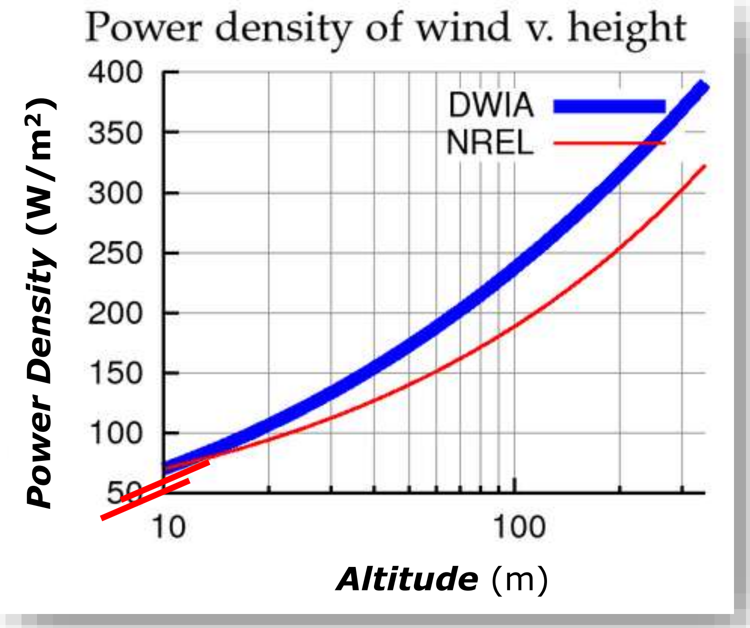
General altitude dependence on wind direction and speed due to combined effect of Coriolis force and friction ("roughness length").

Altitude (z) dependence of wind speed

$$u(z) \approx u_{10m} \cdot (z/10m)^{1/7} \quad and \quad (\rho(z) \approx \rho_0)$$

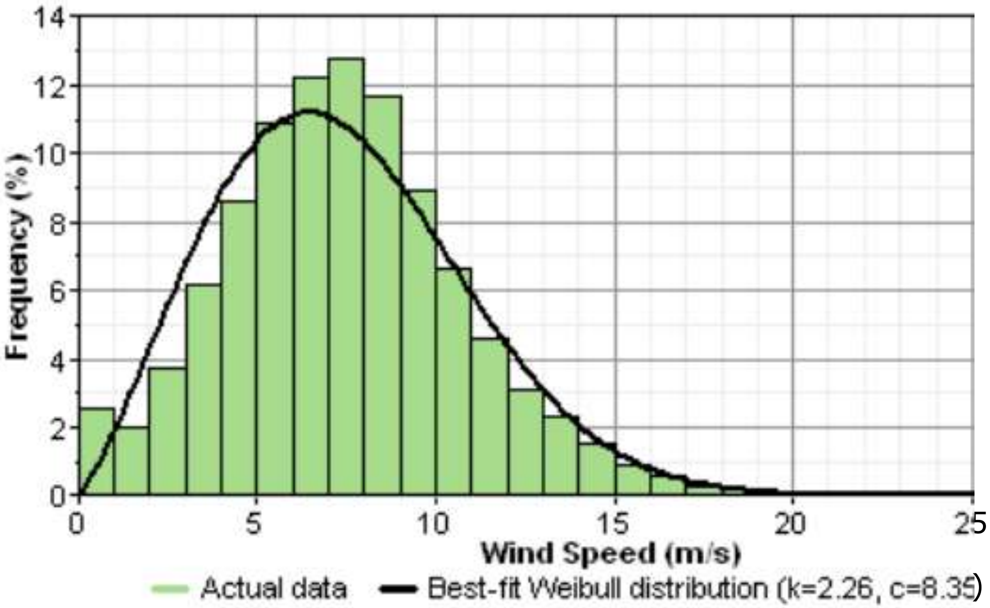
$$\rightarrow \; Power\ density\ P(z) \propto (z/10m)^{3/7}$$

$$P(z) \propto \sqrt{z} \quad \rightarrow initially\ linear,\ then\ weak$$



Wind Speed Distributions

Empirical fit of wind speed distribution dP(u)/du: 2-parameter *Weibull* distribution



$$\frac{dP(u)}{du} = \frac{k}{c}\cdot\left(\frac{u}{c}\right)^{k-1}\cdot\exp\left[-\left(\frac{u}{c}\right)\right]$$

$$\textit{Wind speed } u$$

$$\textit{Shape parameter } k$$

$$c \textit{ scale parameter}$$

$$\textit{Mean wind speed } \langle u\rangle = c\cdot\Gamma\left(\frac{1}{k}+1\right)$$

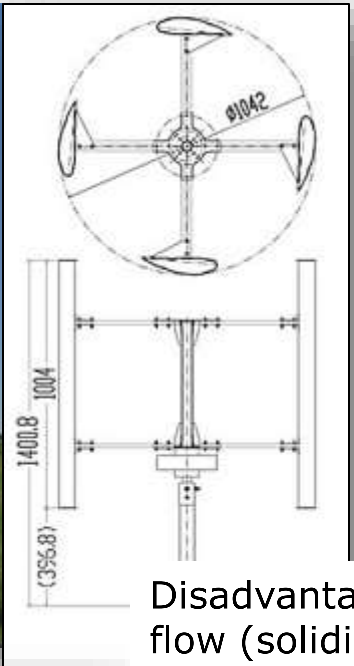
$$\textit{Wind Speed } u\ (m/s)$$

$$\textit{Frequency } (\%),\ \textit{fixed } \Delta u \rightarrow \frac{\Delta P(u_n)}{\Delta u};\quad \textit{Normalization} \sum_n \frac{\Delta P(u_n)}{\Delta u} = 1$$

Tower Design & Aerodynamics

Wind Turbines Designs: Vertical-Axis

Horizontal axis wind turbine

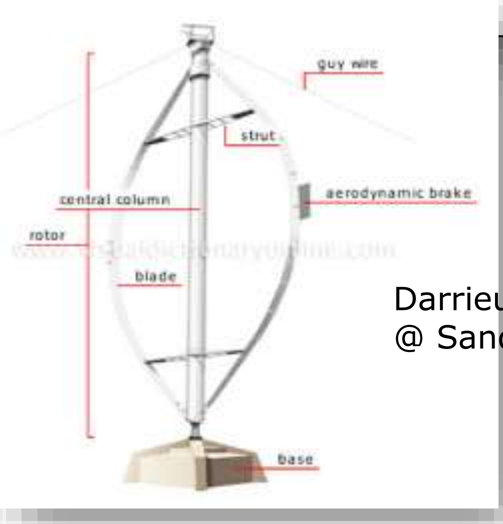


Aerodynamic principles of VAWT are similar: lift and drag on air foil.

Advantage: because of axial symmetry need no yaw drive to optimize for wind direction.

Disadvantage: More resistance to air flow (solidity), heavier & complex rotor,

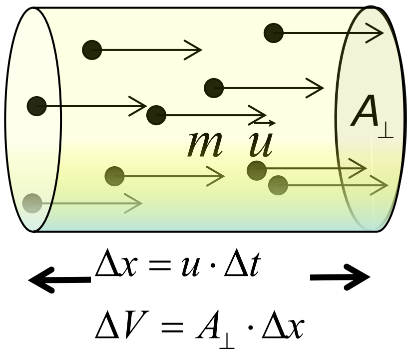
Many different designs, offered by a number of companies for small power outputs (kW) → economically disadvantaged.



Darrieus type VAWT @ Sandia Lab.

Aerodynamics →

Air Resistance/Parasitic Drag



Estimation of parasitic drag, angle of particle flow (wind) relative to area “angle of attack” $\alpha = 90^0$.

Continuous flow of particles (mass m),

Number density $\rho\ \left[\#/cm^3\right]$, *mass density* $\rho_m = m \cdot \rho$

Mass flux density : $j_m(u) = m \cdot \underbrace{\rho \cdot u}_{j(u)} = \rho_m \cdot u\ \left[g/cm^2 \cdot \Delta t\right]$

Wind speed $u = u_\perp$ (⊥ *to area* A) → *Kinetic energy density* $e_{kin} = \frac{1}{2} m \cdot \rho \cdot u^2$

Energy flux per Δt *onto area* $A = A_\perp$ (⊥ *to wind direction*) :

$$\Delta E = \frac{1}{2}\left(m \cdot \rho \cdot u^2\right) \cdot \underbrace{\left(A \cdot u \cdot \Delta t\right)}_{\Delta V} \rightarrow \text{Power } P = \frac{1}{2} A \cdot m \cdot \rho \cdot u^3 \rightarrow \boxed{P = \frac{1}{2} A \cdot \rho_m \cdot u^3}$$

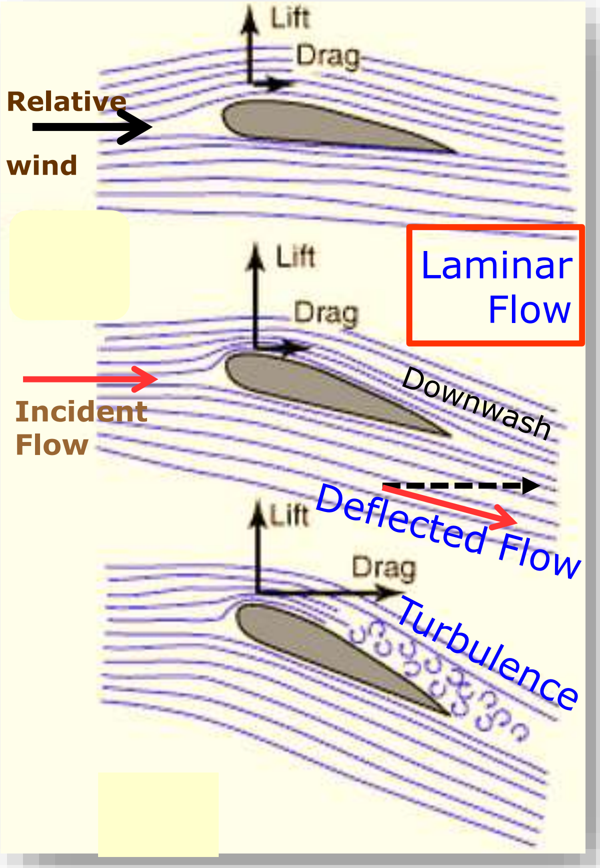
Get force exerted on area A from : $P = F \cdot u \rightarrow F =: F_{drag}$ $\boxed{F_{drag} = \frac{1}{2} A \cdot \rho_m \cdot u^2}$

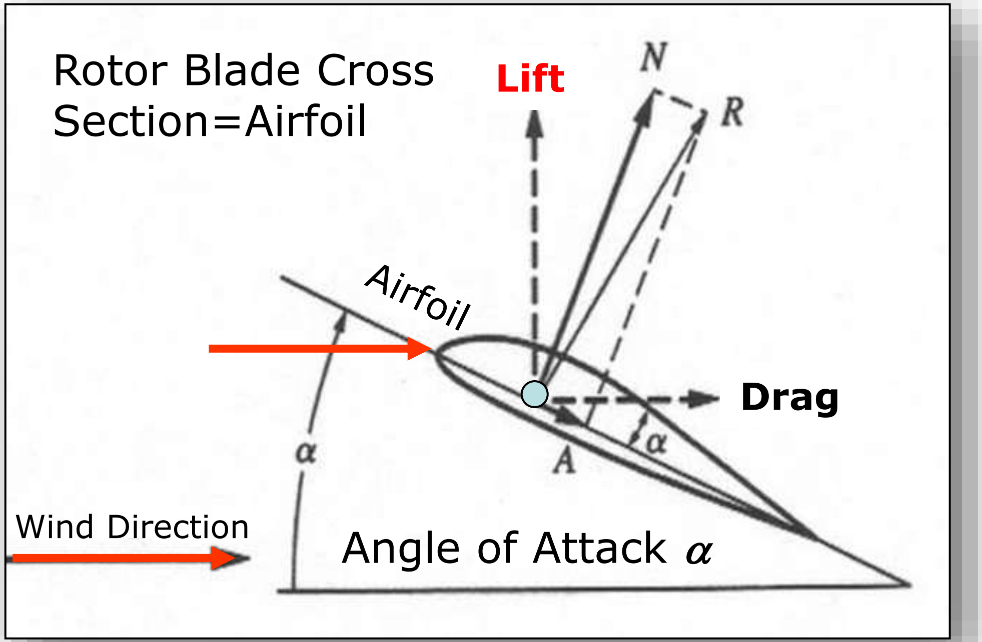
Effective (projected) area hit directly by wind : $A_\perp = C_d \cdot A_{total}$

$$\boxed{\begin{aligned} F_{drag} &= D = \frac{1}{2} C_d \cdot A_{total} \cdot \rho_m \cdot u^2 \\ F_{lift} &= L = \frac{1}{2} C_L \cdot A_{total} \cdot \rho_m \cdot u^2 \end{aligned}}$$

Derivation valid for parasitic drag, e.g., air resistance. Often, experimentally determined **Drag Coefficients** represent total drag/resistance.

Aerodynamics: Lift and Drag on Airfoils

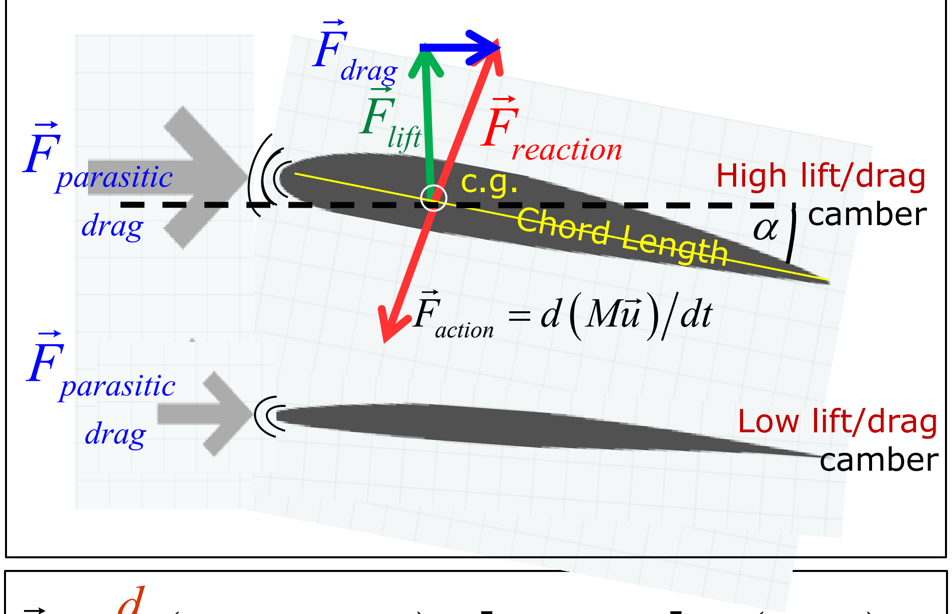




Maximum lift at laminar (steady) air flow around foil at high angle of attack. Flow direction changed by airfoil.
Large angles of attack α → boundary layer (streamlines) separates from air foil, generate turbulence and loss of lift → stall.

Airstream Deflection by Airfoils

$\rho_\# =$ air # density, $u =$ air speed, $A =$ wing area $\perp$ wind



$$\vec F = \frac{d}{dt}(air\,mass\cdot\vec u) = [\rho_\# \cdot u \cdot A]\cdot d(m\cdot\vec u)$$

$$Momentum\ change\ dp = m\cdot u\cdot\sin\alpha$$

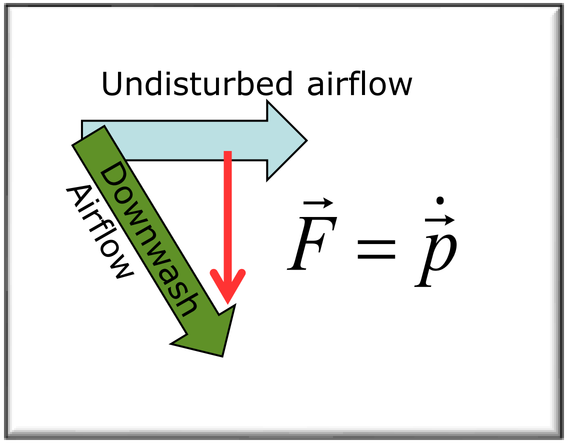
$$Lift\ force:\ F_{lift} = \boxed{L = C_L(\alpha)\cdot\frac{1}{2}(\rho_m\cdot A\cdot u^2)}$$

$$\to \vec F_{reaction} = -\vec F_{action} = \vec F_{lift} + \vec F_{drag}$$

$Air\ flow\ density\ J = \rho_\# \cdot u\ (particles/s\cdot m^2)$

$Energy\ density\ E/V = (1/2)m\cdot\rho_\# u^2\ (J/m^3)$

Deflecting air stream→Newton's Law

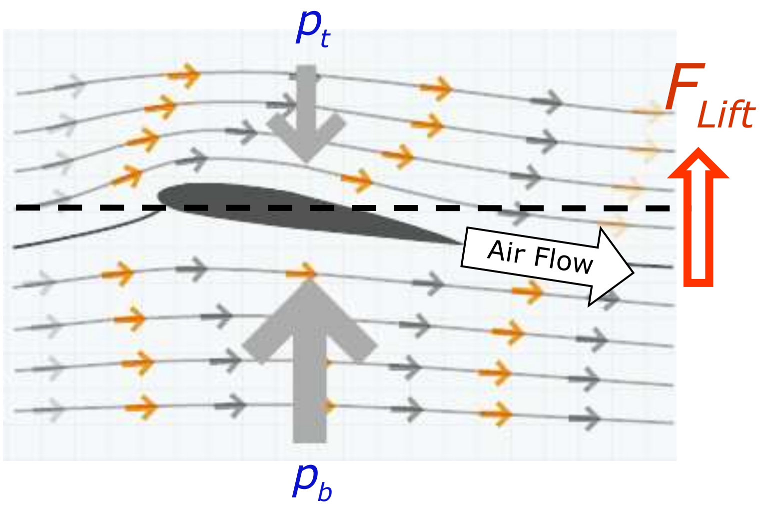


Lift depends on asymmetric shape (camber) and incline (angle of attack α) of air foil relative to air flow. Air stream deflected downwards.

Low lift camber requires high speed to generate lift.

Airstream Pressure Differential by Airfoils

Reduced static pressure on top
Bernoulli's Principle → partial lift



Additional (lesser) lift & drag source:

Difference in Bernoulli pressures between above and below airfoil.
Depends on curvature of the "camber"
→ force differential

$$p_t + (1/2)\,\rho_m \cdot u_t^2 = p_b + (1/2)\,\rho_m \cdot u_b^2$$

$$\frac{F_{Lift}}{A} = p_b - p_t = \frac{1}{2}\rho_m\left[u_t^2 - u_b^2\right]$$

$$F_{Lift} \propto A \cdot \bar{u} \cdot \Delta u(\alpha,\ldots); \quad \Delta u \approx \alpha \cdot \bar{u}$$

$$Lift\ force: F_{Lift} = \boxed{L = C_L \cdot A \cdot \left(\frac{1}{2}\rho_m \cdot u^2\right)} \quad \begin{array}{c} depends \\ on\ (wind\ speed)^1 \end{array}$$

$C_L = coefficient\ of\ lift\ \ A = A(\alpha) = total\ airfoil\ (wing)$
$area\ facing\ wind\ (\perp)\ with\ relative\ speed\ u\ \ (really\ \Delta u)$

Lift depends on shape (camber) and incline (angle of attack α) of air foil relative to air flow. Air stream deflected downwards.

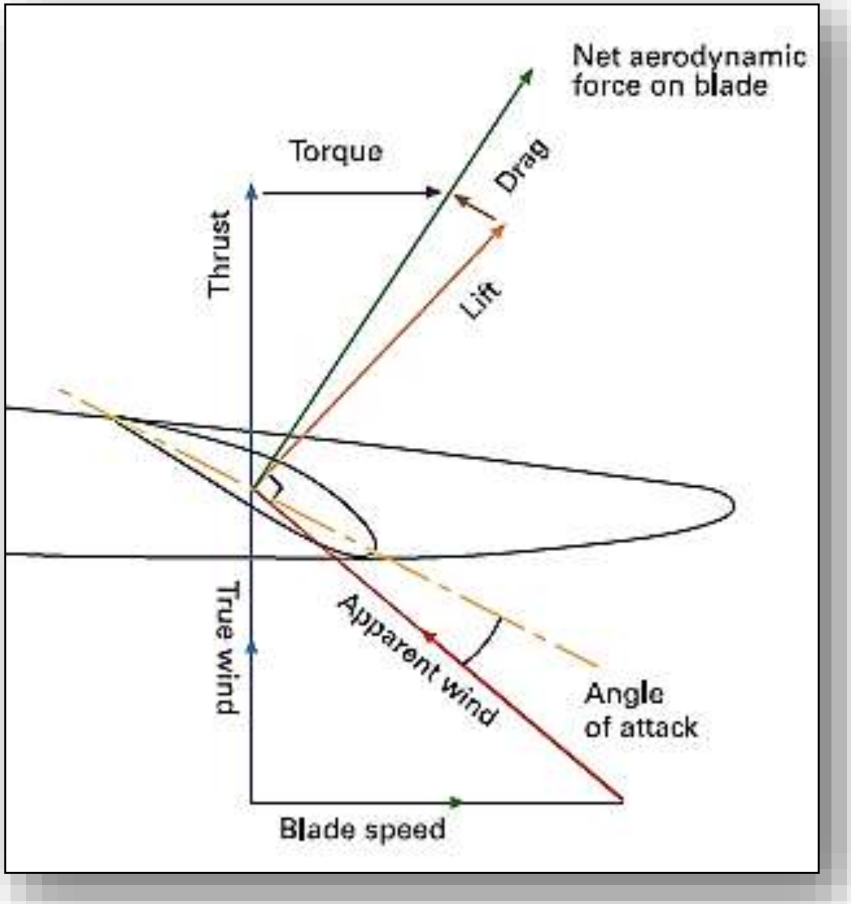
Most Popular Aerodynamic Blade Profile

Velocity u_B of blade relative to air increases with radial distance r from hub → lift increases with r for a given angle of attack → mechanical strain.

For constant blade profile:

1) Lift is low close to root, large at tip.
2) Narrowing required by hub/nacelle.
3) Effective angle of attack decreases with r → loss of lift @v =const. efficiency.

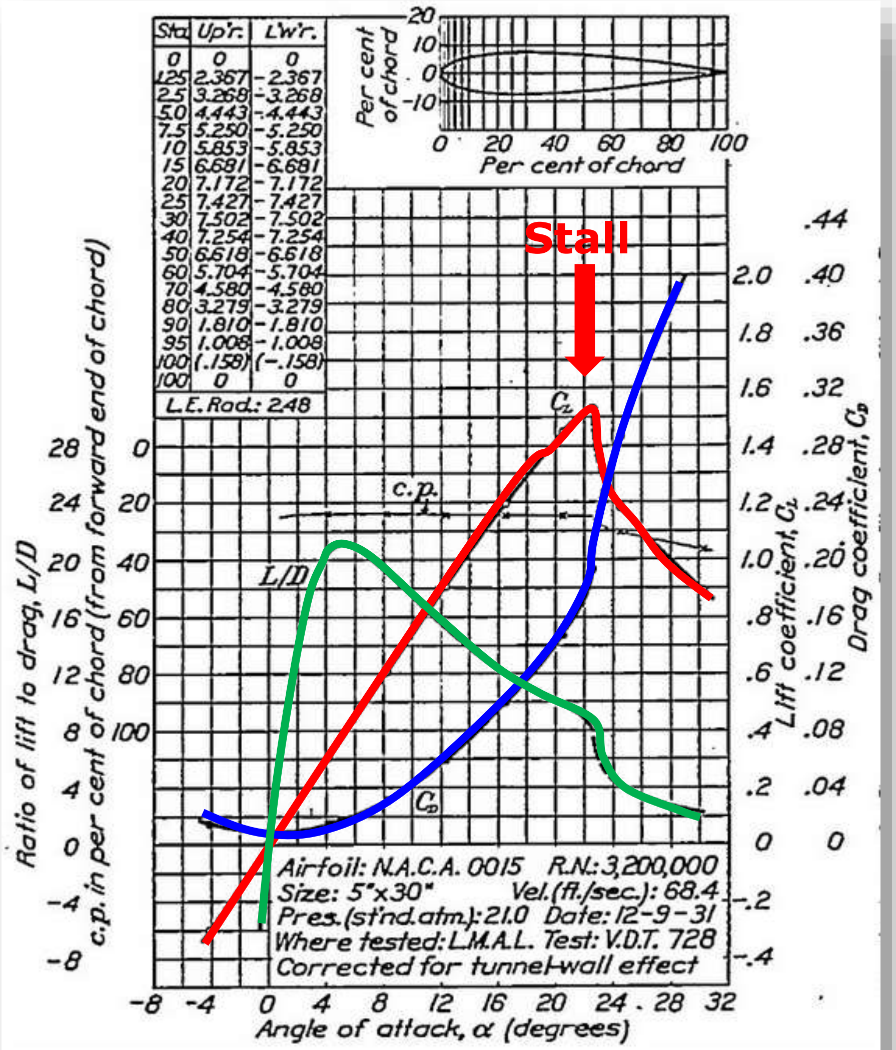
Relative wind direction & speed



Remedy:

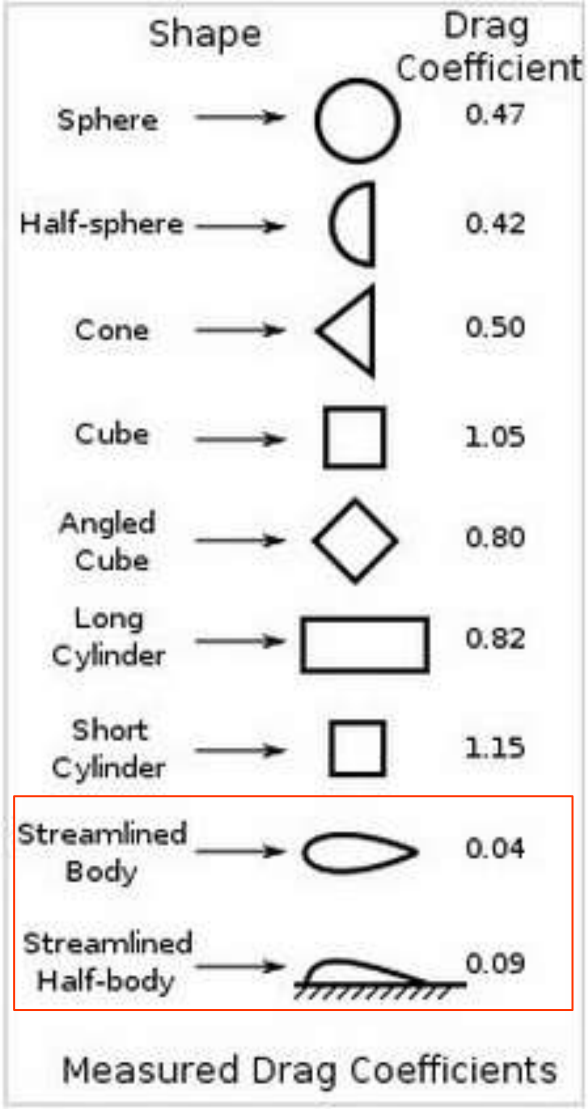
1) Use larger chord close to root.
2) Twist blade by 10^0 -20^0 from root to tip.

Lift vs. Drag Compromise



Full set of wind tunnel data and full report
NACA-460 1933 78 airfoils

NASA wind tunnel measurements.



Shape		Drag Coefficient
Sphere →		0.47
Half-sphere →		0.42
Cone →		0.50
Cube →		1.05
Angled Cube →		0.80
Long Cylinder →		0.82
Short Cylinder →		1.15
Streamlined Body →		0.04
Streamlined Half-body →		0.09

Measured Drag Coefficients