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

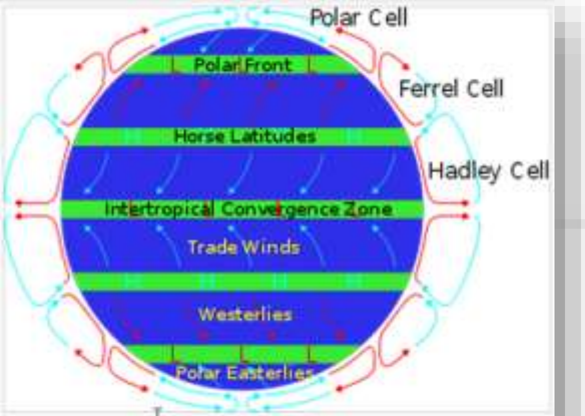
First US Wind Farms

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.

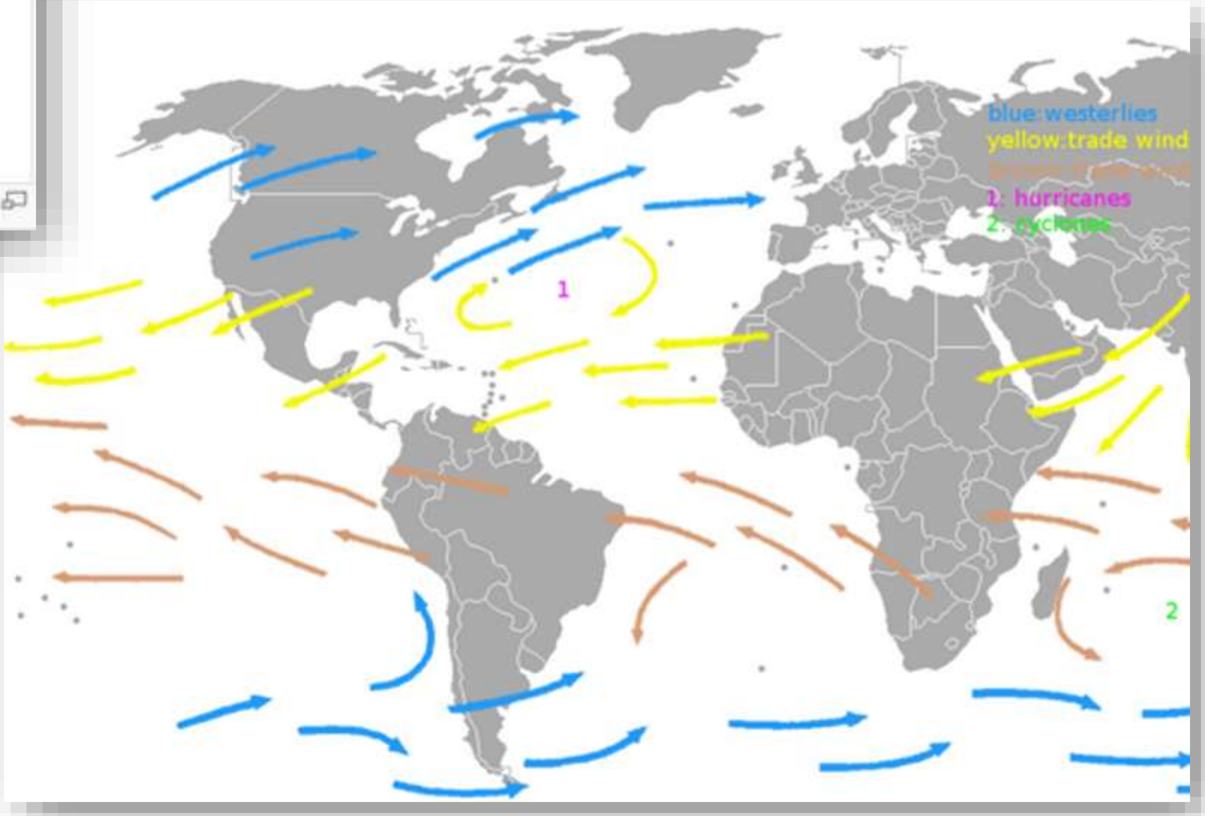
Entire project has been rebuilt with newer turbines.

Global Wind Patterns



The six major wind belts

Latitudinal variation of solar insolation → Equator updraft
S → N upper air flow destabilized by **Coriolis** force
(deviation to right on northern hemisphere)
→ Pattern breaks up into 3 regions (cells) per hemisphere.



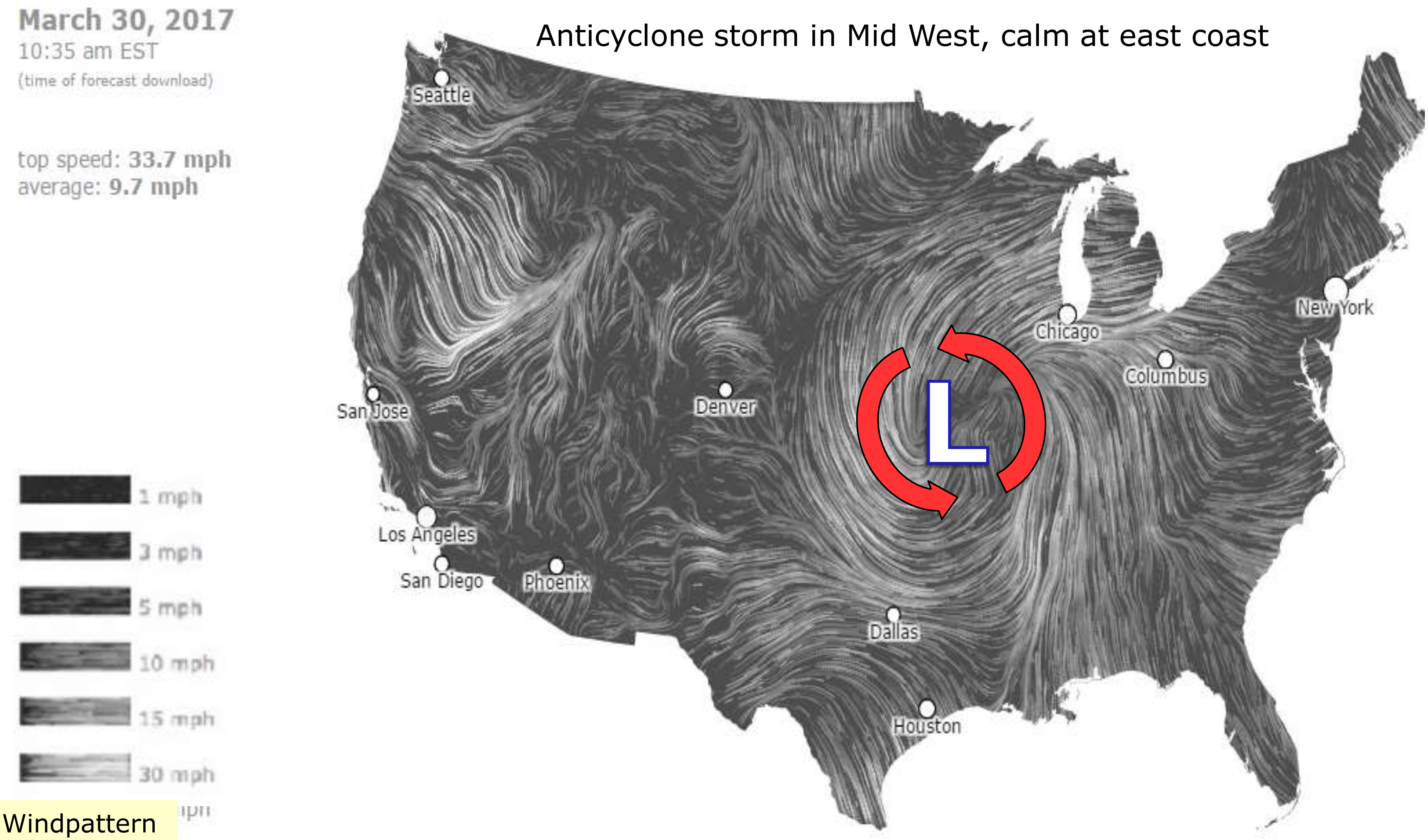
Westerlies and NE trade winds near 30^0 latitudes. High-altitude jet stream (v > 300 km/h)

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

Anticyclone storm in Mid West, calm at east coast



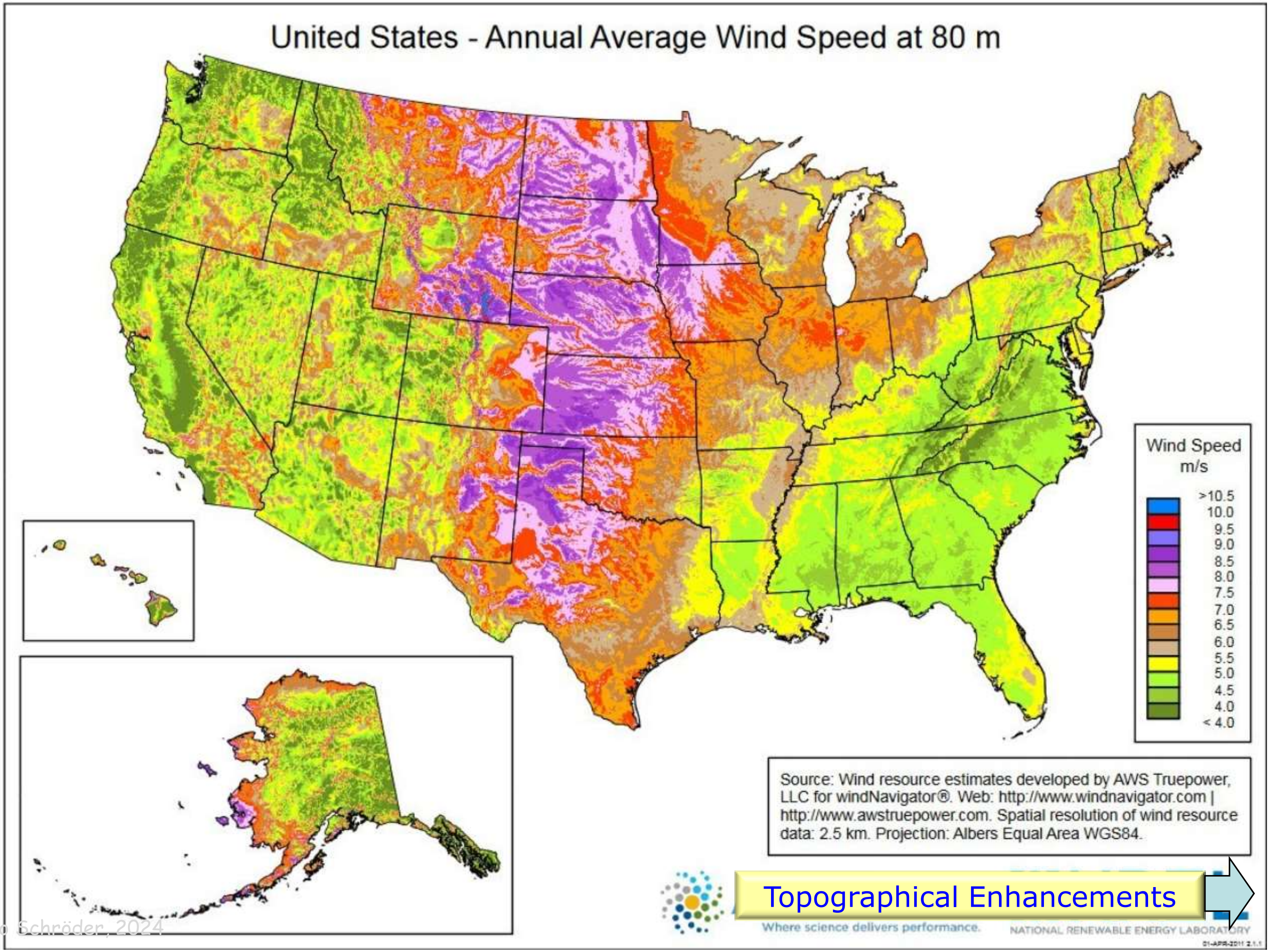
March 30, 2017
10:35 am EST
(time of forecast download)

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

Windpattern animation

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

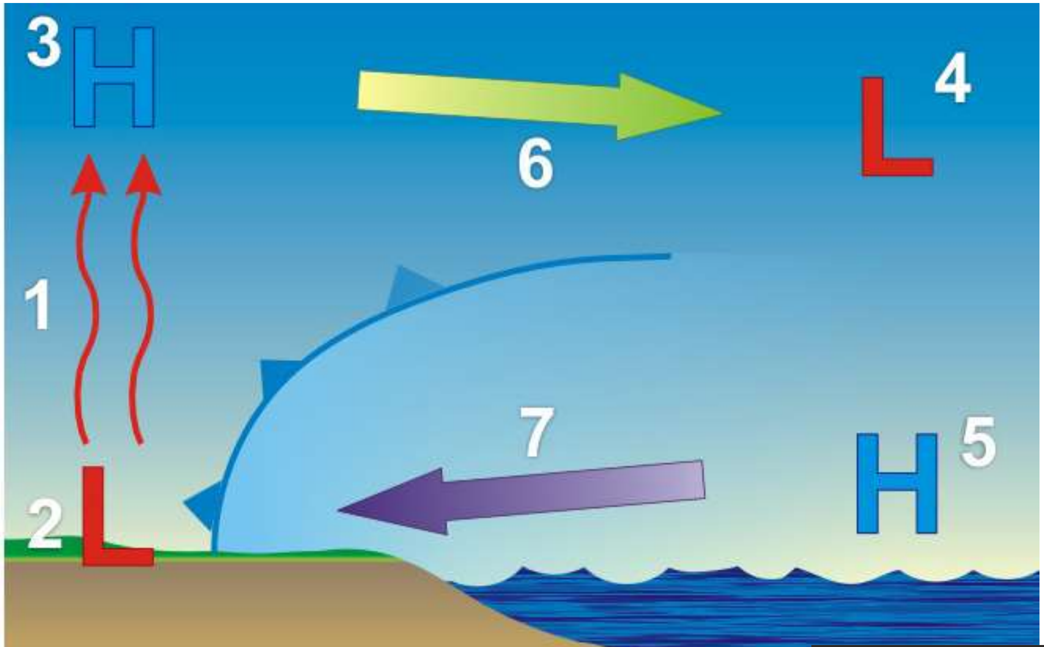
US Wind Resources Potential



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

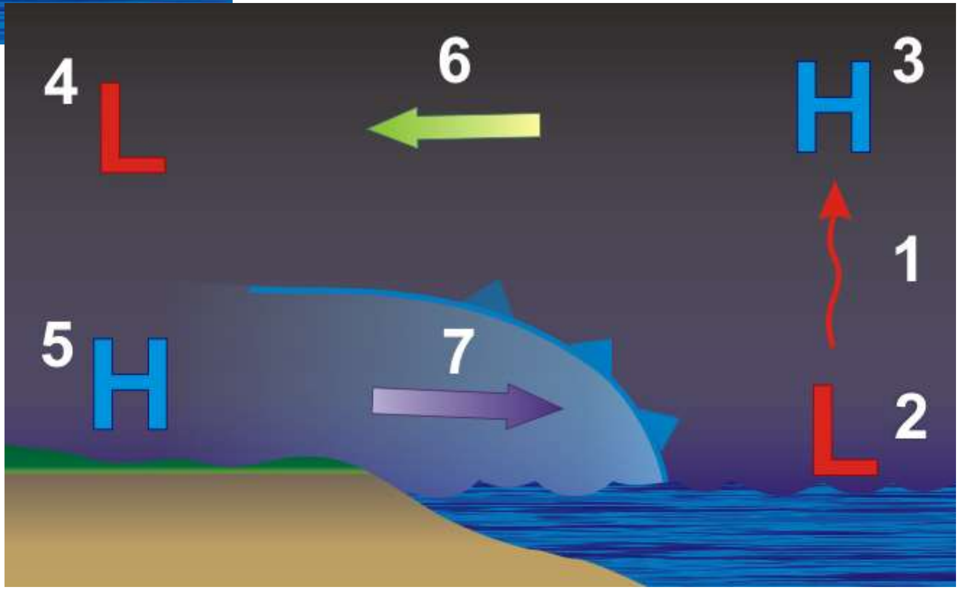
Sea Breeze-Land Breeze



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.

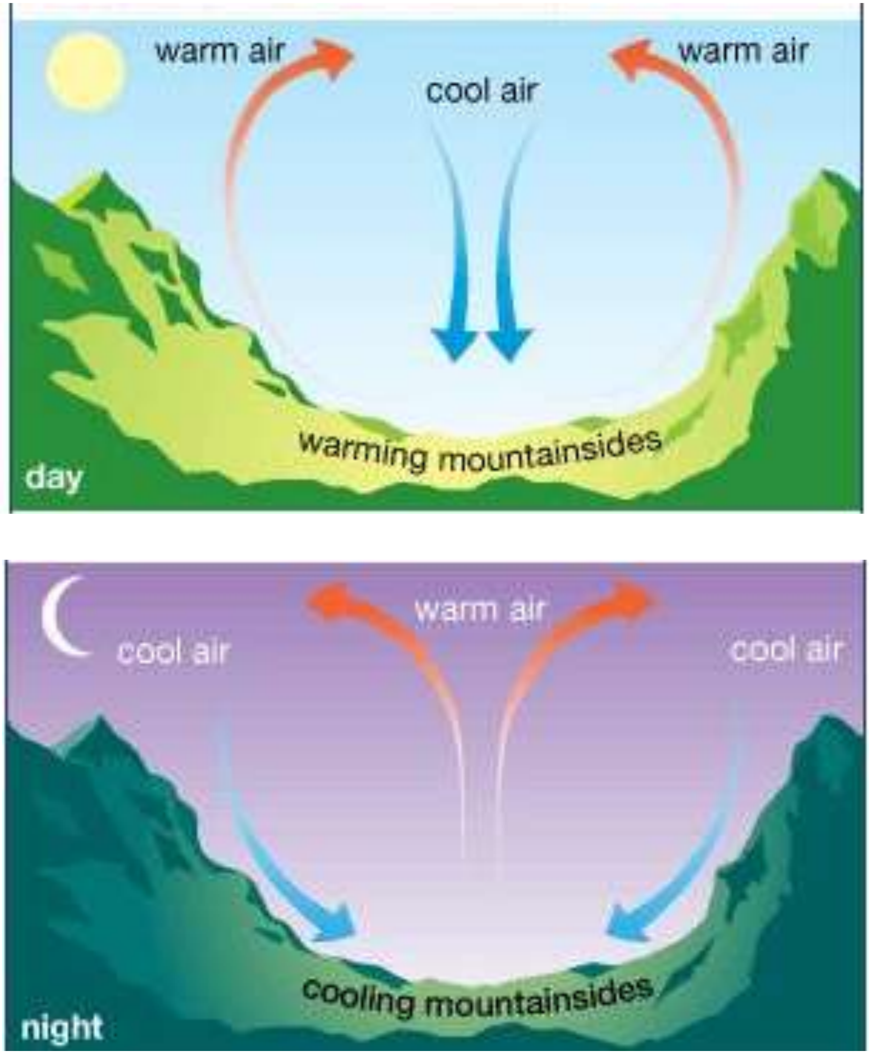
Day-time: Sea breeze 7
Return flow 6.



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

- Global & local wind resources/patterns

Reading Assignments

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

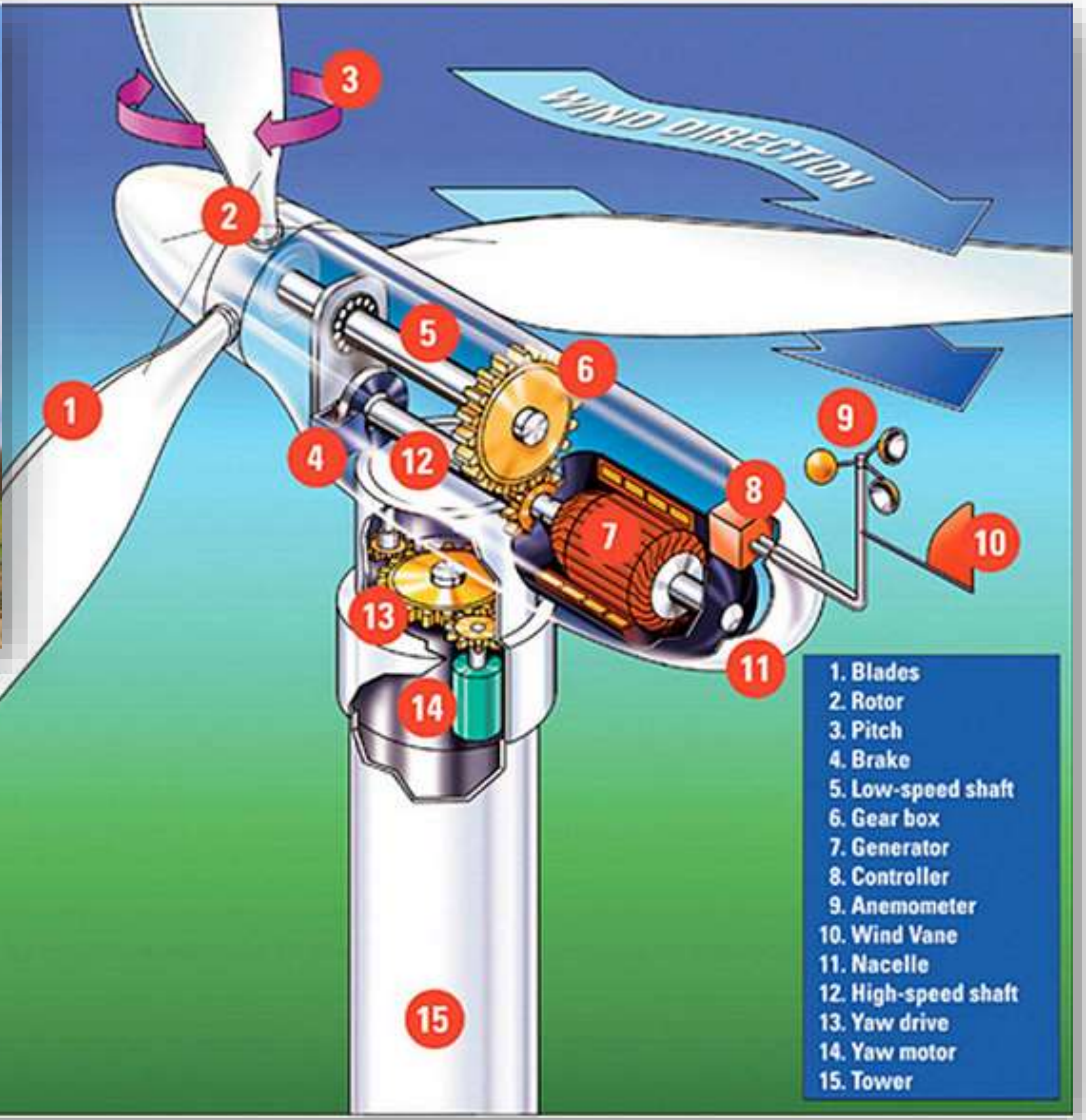
Wind power in national and international energy mix

Basic Wind Tower Construction

17th-century windmill (Northern Germany).

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

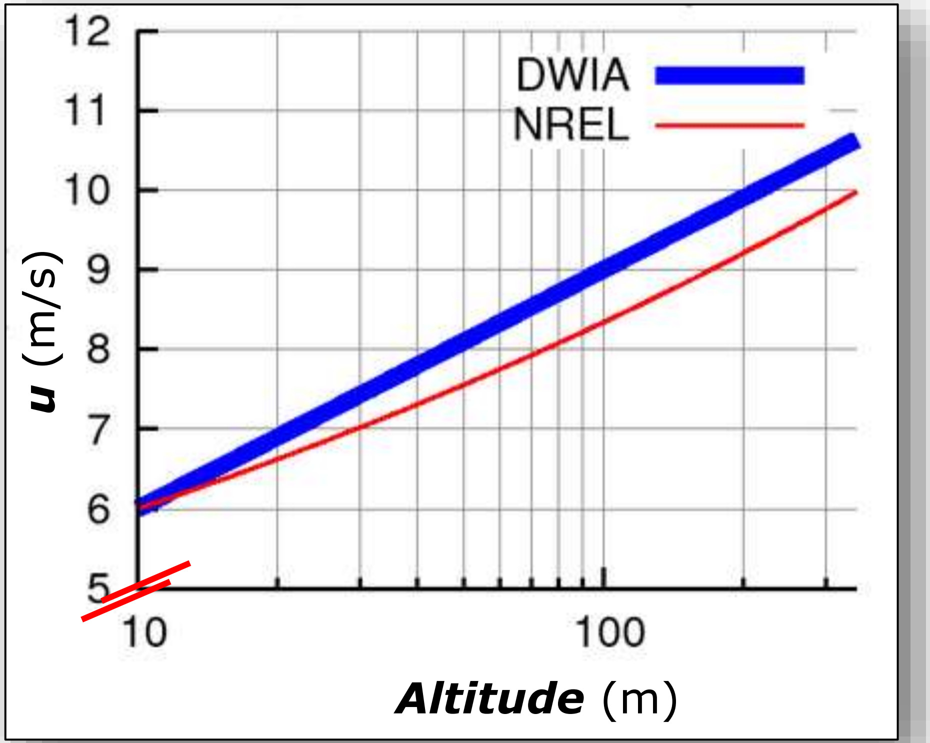
Modern rotor blades are aerodynamically optimized (“airfoils”).



Giant Wind Towers: Offshore Windfarm

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

Altitude Dependence of Mean Wind Speed



Altitude (z) dependence of wind speed

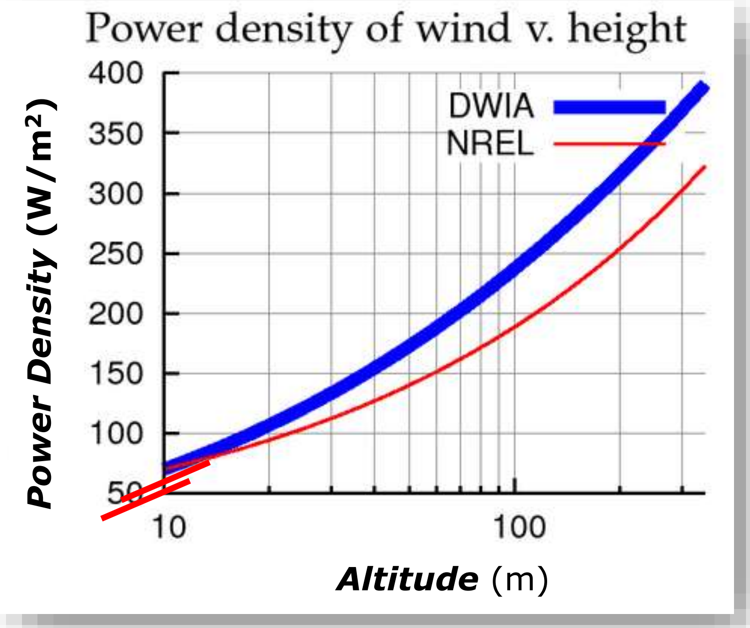
$$u(z) \approx u_{10m} \cdot (z/10m)^{1/7} \quad and \quad (\rho(z) \approx \rho_0)$$

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

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

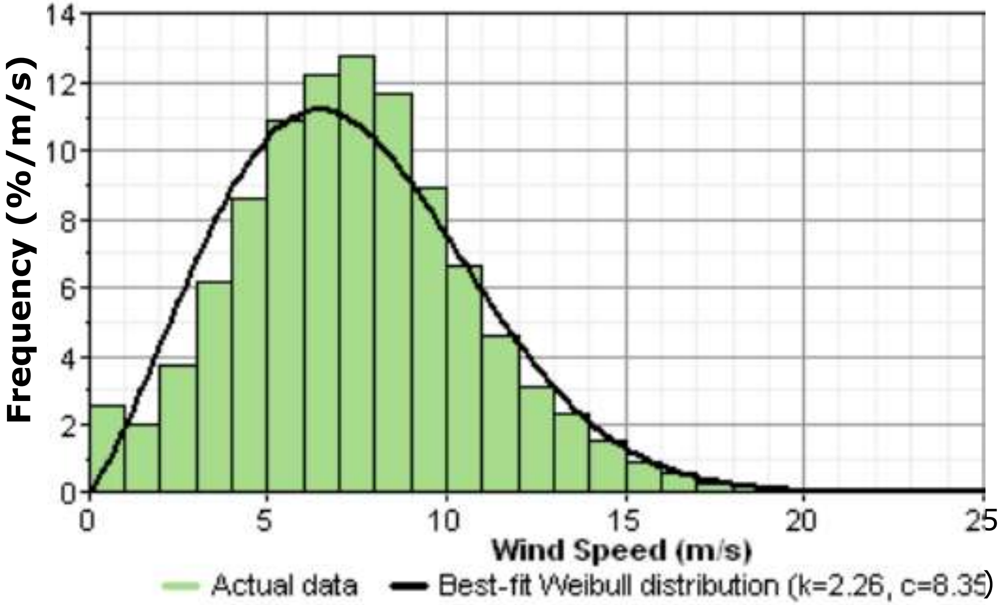
Close to ground level, uneven landscape (buildings, trees, power lines) produces friction & turbulent wind patterns (wind shear) = obstacles to laminar flow.

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



Wind Speed Distributions

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



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

Wind speed u

Shape parameter k

c scale parameter

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

Γ = *gamma function*

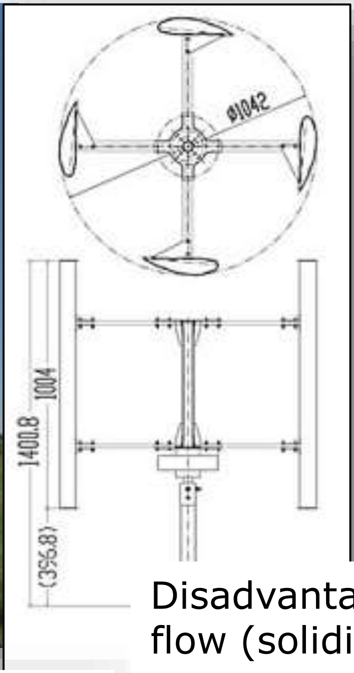
$$\text{Wind Speed } u\ (m/s)$$

$$\text{Frequency } (\%),\ \text{fixed } \Delta u \rightarrow \frac{\Delta P(u_n)}{\Delta u};\quad \text{Normalization } \sum_n \frac{\Delta P(u_n)}{\Delta u} = 100\%$$

Tower Design & Aerodynamics

Wind Turbines Designs: Vertical-Axis

Horizontal axis wind turbine

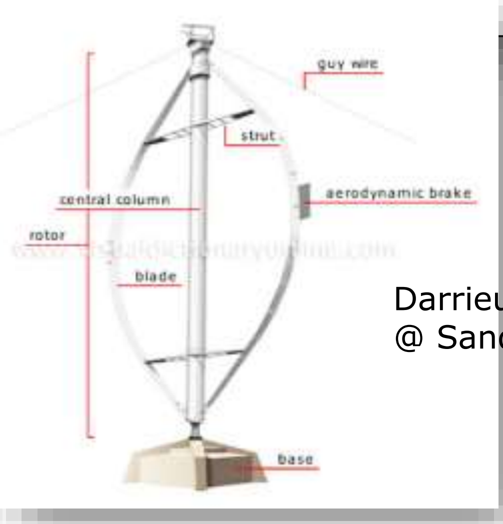


Aerodynamic principles of VAWT are similar: lift and drag on air foil.

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

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

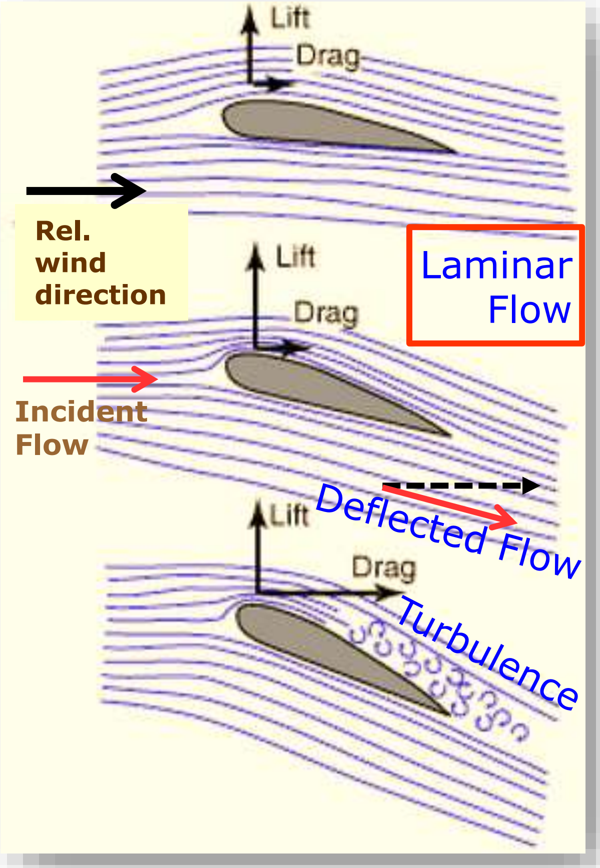
Many different designs, offered by a number of companies for small power outputs (kW) → so far economically disadvantaged.

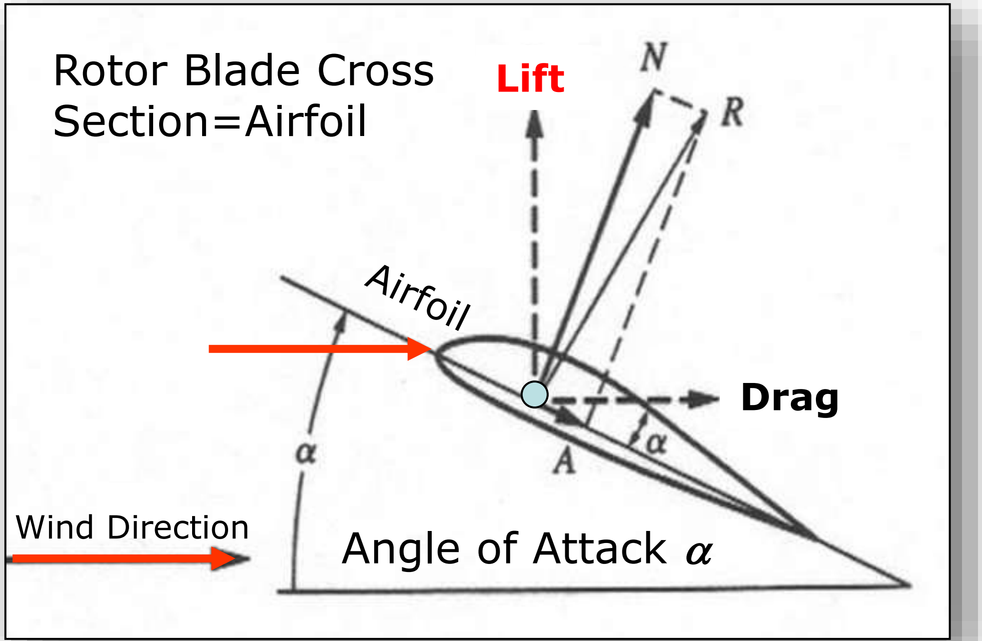


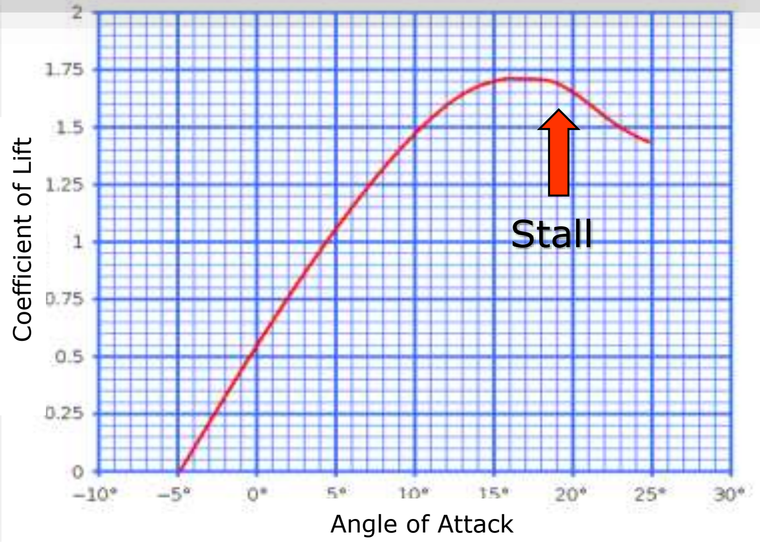
Darrieus type VAWT
@ Sandia Lab.

Aerodynamics

Aerodynamics: Lift and Drag on Airfoils



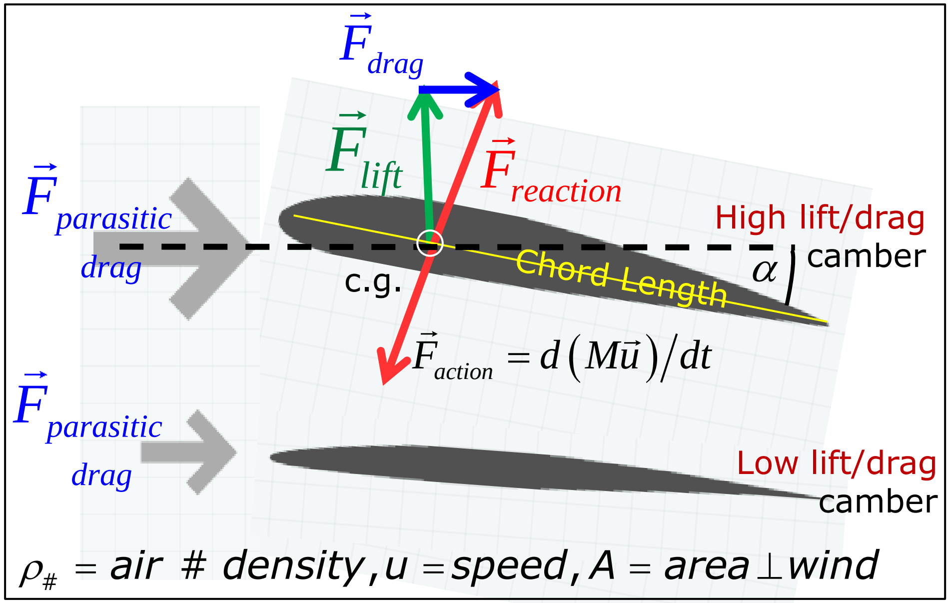




Maximum lift at laminar (steady) air flow around foil at high angle of attack. Flow direction changed by airfoil.

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, $u =$ speed, $A =$ area $\perp$ wind

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

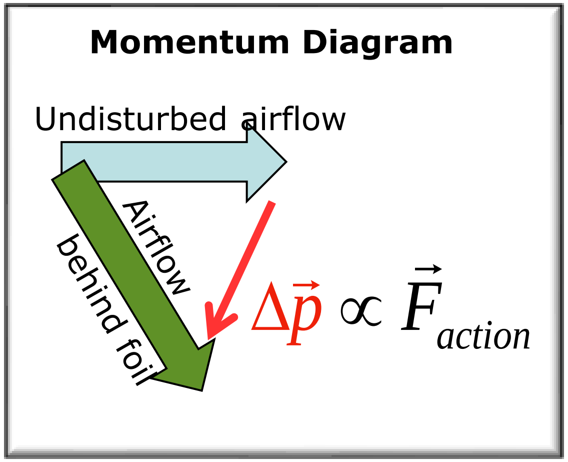
$$Momentum\ change\ dp = m \cdot u \cdot \tan\alpha$$

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

$$\rightarrow \vec{F}_{reaction} = -\vec{F}_{action} = \vec{F}_{lift} + \vec{F}_{drag}$$

Lift is generated mostly as reaction to downward deflection of air mass: action=reaction

Newton's Law

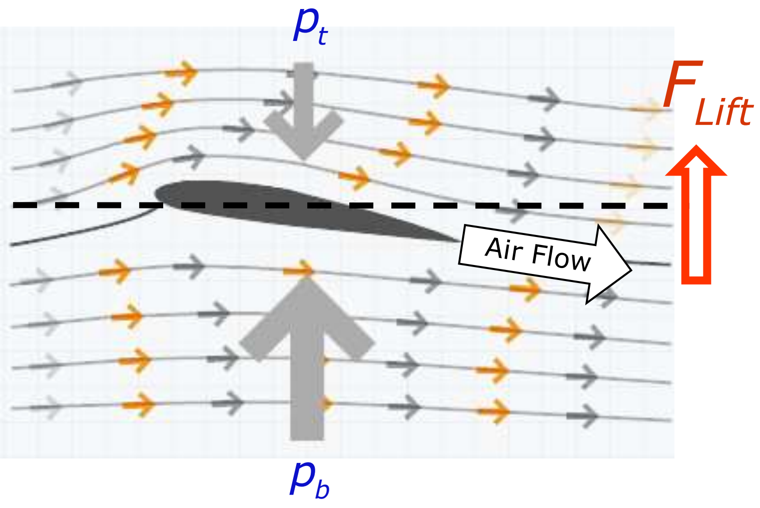


Lift depends on asymmetric shape (camber) and incline (angle of attack α) of air foil relative to air flow. Air stream deflected downwards.

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

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

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

$$F_{Lift} \propto A \cdot \Delta u(\alpha,\ldots) \cdot \bar{u} > 0$$

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

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

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

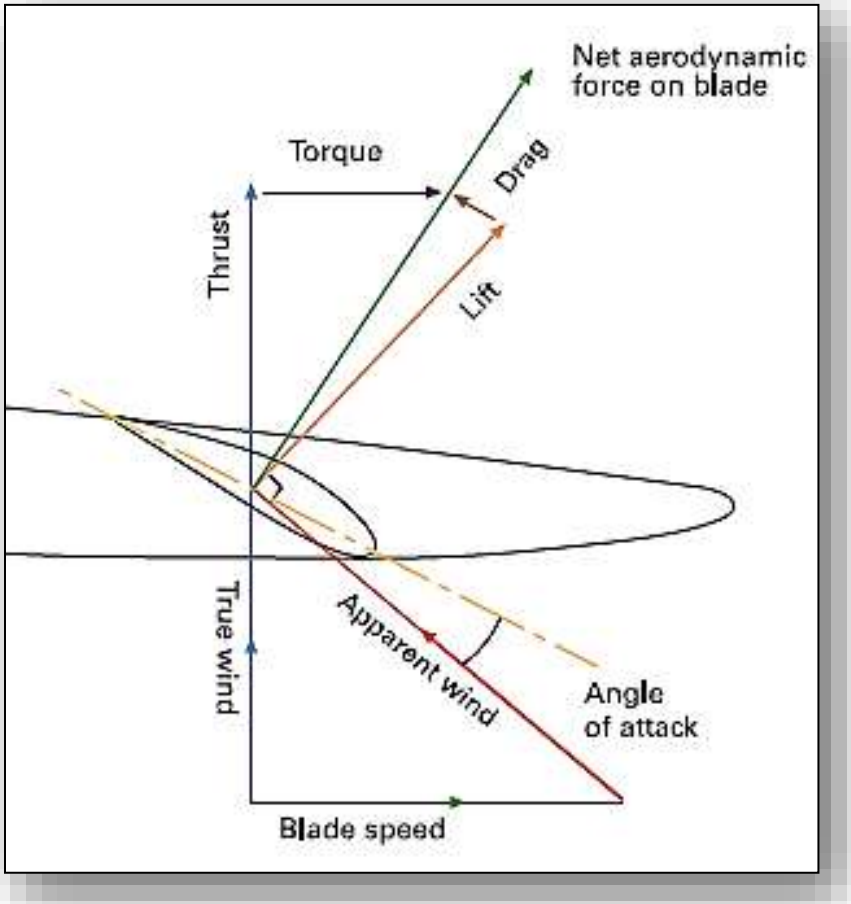
Most Popular Aerodynamic Blade Profile

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.

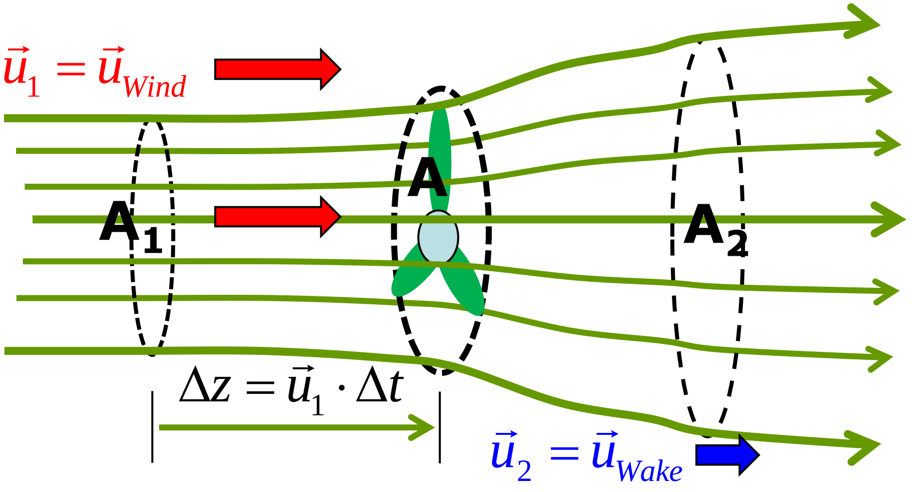
Relative wind direction & speed



Remedy:

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

Aerodynamic Power Transfer



At turbine (obstacle), u slows, stream-lines diverge, wind speed decreases, $\mathbf{u_2} = \mathbf{u_{wake}} < \mathbf{u_1} = \mathbf{u_{wind}}$

$$E_{kin} = \frac{1}{2}\cdot\left(\rho_m \cdot \Delta V\right)\cdot u_1^2$$

volume ΔV *moves through* A *in* Δt:

Volume $\Delta V\left(u_1\right) = A\cdot u_1 \cdot \Delta t$.

Power flux $\perp A$: $\boxed{P_i = \frac{\Delta E_{kin}}{\Delta t} = \frac{1}{2}\cdot\left(\rho_m \cdot A_i \cdot u_i^{3}\right)}$ Power in wind flow, before: *i=1*

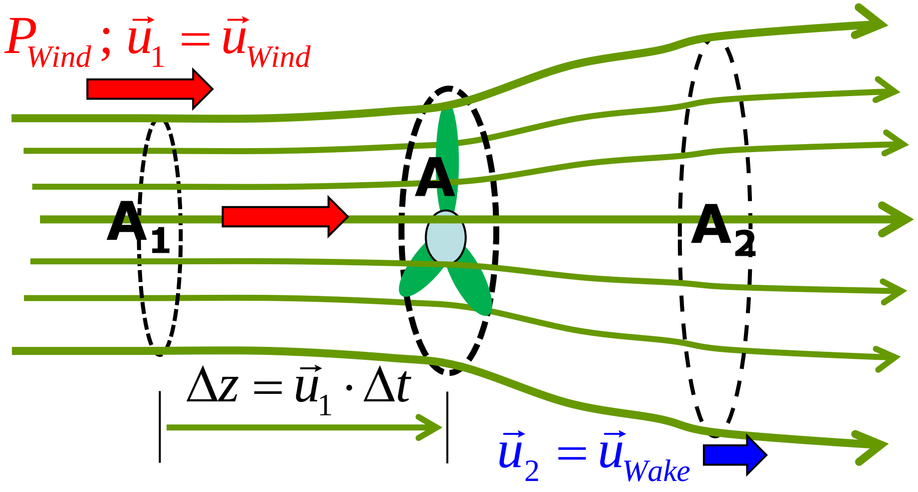
Continuity: $j_1 A_1 = \rho A_1 \cdot u_1 \approx \rho A_2 \cdot u_2 = j_2 A_2$ → Use mean *u for* mass flow during Δt

$\rightarrow$ *Average speed* $\bar{u} := \left(u_1 + u_2\right)/2$ *for mass flow* $\dot{M} = \rho_m \cdot \Delta V/\Delta t = \rho_m A \bar{u}$

Volume $\Delta V\left(\bar{u}\right)$ *transfers power differential to turbine*

$$\Delta P = P_1 - P_2 \approx \frac{\left(\rho_m A \bar{u}\right)}{2}\left(u_1^2 - u_2^2\right) = \frac{\left(\rho_m A\right)}{4}\left(u_1 + u_2\right)\left(u_1^2 - u_2^2\right) \rightarrow =: C_{Turbine} P_{wind}$$

Aerodynamic Power Transfer



At turbine (obstacle), u slows, stream-lines diverge, wind speed decreases, $\mathbf{u_2 = u_{wake} < u_1 = u_{wind}}$

$$E_{kin} = \frac{1}{2}\cdot\left(\rho_m \cdot \Delta V\right)\cdot u_1^2, \quad volume\ \Delta V$$

$$through\ A\ in\ \Delta t:$$

$$Volume\ \Delta V\left(u_1\right) = A \cdot u_1 \cdot \Delta t.$$

$$Delivered\ to\ turbine: \boxed{\Delta P =: C_{Turbine} P_{wind}}\ defines\ \boxed{power\ coefficient\ C_{Turbine}} \rightarrow$$

$$C_{Turbine} \approx \frac{1}{2u_1^3}\cdot\left(u_1 + u_2\right)\cdot\left(u_1^2 - u_2^2\right) = \frac{1}{2}\cdot\left(1+x\right)\cdot\left(1-x^2\right) \quad with\ \ x := \frac{u_2}{u_1}$$

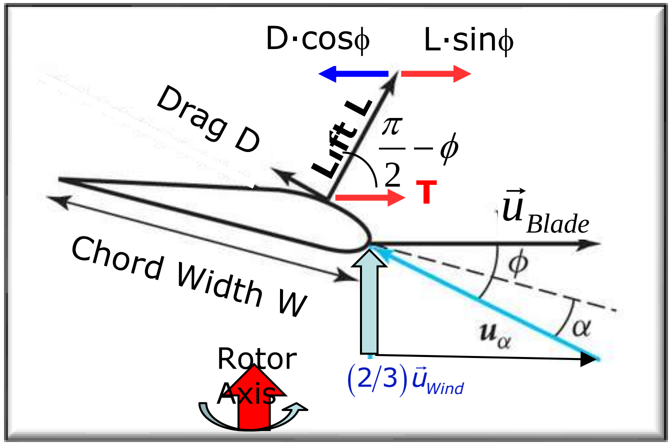
$$Maximum\ \ power: d\left(\Delta P\right)/dx = 0 \ \rightarrow x\big|_{\Delta P=\max} = 1/3 \rightarrow self\ \ regulating\ \ stable$$

$$Effective\ mean\ speed\ \boxed{\bar{u} := \frac{1}{2}u_1\left(1+x\right) = \frac{2}{3}u_1}$$

$$\boxed{C_{Turbine} = \frac{\Delta P}{P_{Wind}} \leq \frac{16}{27} = 0.593 \quad \begin{matrix} Betz \\ Limit \end{matrix}}$$

$$\bar{u} := \left(1-a\right)u_{Wind} \qquad a = linear\ \left(axial\right)\ induction\ \ factor\ of\ \ turbine = f\left(\#blades, A_i\right)$$

Lift Induced Drag



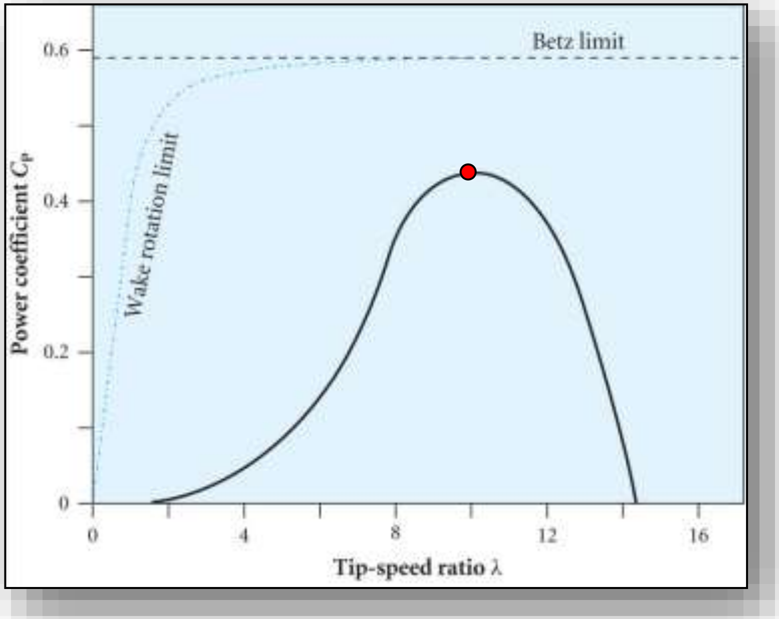
For an air foil exposed to an air flow, there is always an induced drag associated with lift countering thrust:

$$L = \frac{1}{2}C_L\cdot(\rho_m\cdot A)\cdot\bar{u}^2, \qquad D = \frac{1}{2}C_d\cdot(\rho_m\cdot A)\cdot\bar{u}^2$$

Effective force (thrust) is ⊥ rotation axis

$$L_{eff} = L\cdot\sin\phi - D\cdot\cos\phi = L\cdot\sin\phi\left[1-\left(\frac{C_d}{C_L}\right)\cdot\cot\phi\right]$$

$$\textit{Drag/lift ratio}: \quad g = C_d/C_L$$



Long air foil (propeller/rotor blade)→ large changes in effective wind speed.
Equalize blade loading by chord/camber variationalong foil.

$$\text{"Twist" angle}: \quad \cot\phi(r) = \left(\frac{3\lambda}{2R}\right)\cdot r \quad \textit{Large near tip}$$

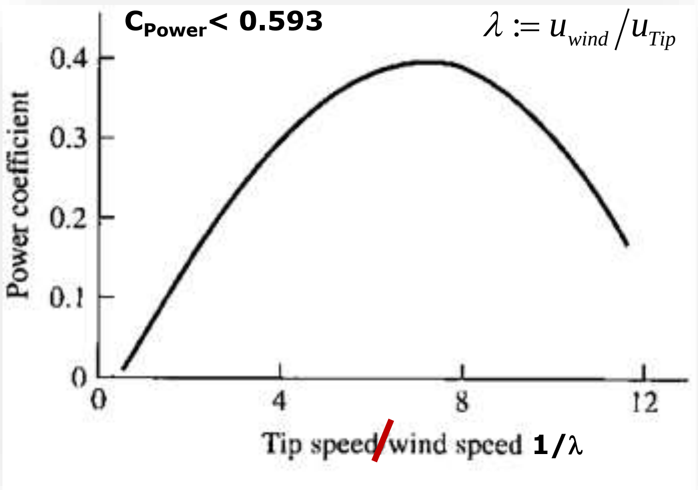
$$\textit{Use typical / representative } r \approx (2/3)\cdot R \rightarrow \cot\phi \approx \lambda$$

$$L_{eff} \sim L\cdot\sin\phi\cdot[1-g\cdot\lambda] \rightarrow$$

$$\boxed{C_{Power} \leq C_{Betz}\cdot[1-g\cdot\lambda]}$$

Modern turbines: g ~ 0.02, λ ~ 10

Operational Turbine Power Limits



Operational range of turbines

$u_{cut\text{-}in} \le u_{Wind} \le u_{cut\text{-}out}$

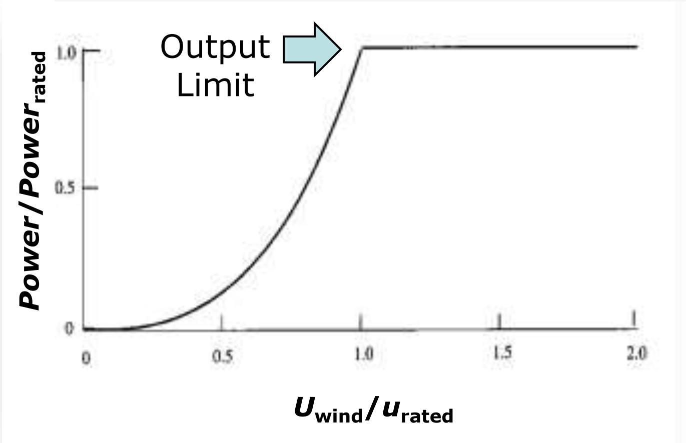
Large range is not economical: electric generator has rotational (power output, frequency) requirements and limitations.

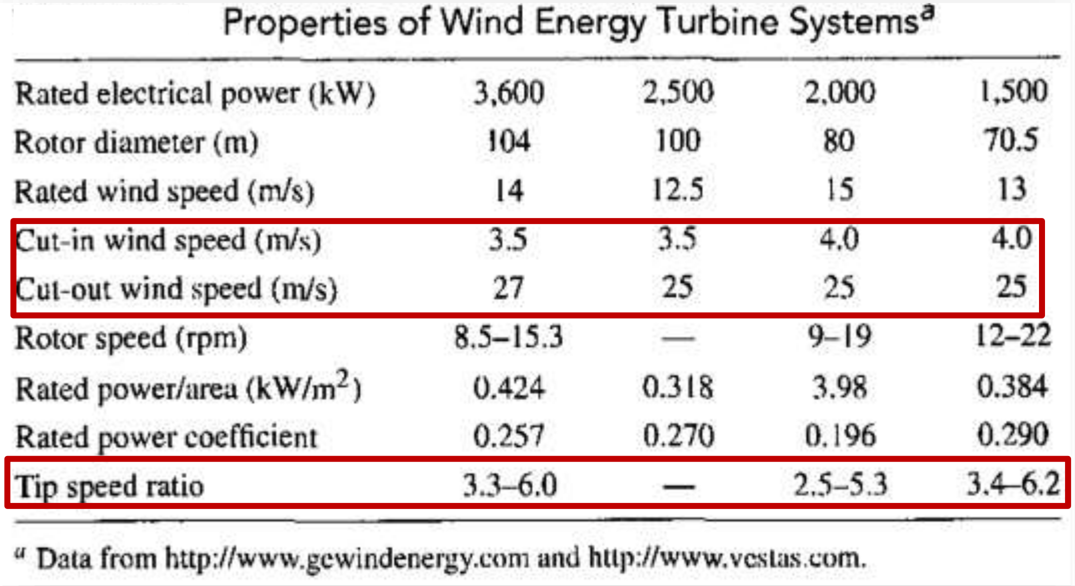
→ Rated (nominal) wind speed $u_{rated} \approx u_{cut\text{-}out}/2$

→ Blades pitch (feather) if $u_{wind} > 2 \cdot u_{rated}$.

Capacity factor ***CF***$:=\langle Power \rangle_{time} / Power_{rated}$.

Typical: ***CF*** ≈ 0.2-0.4





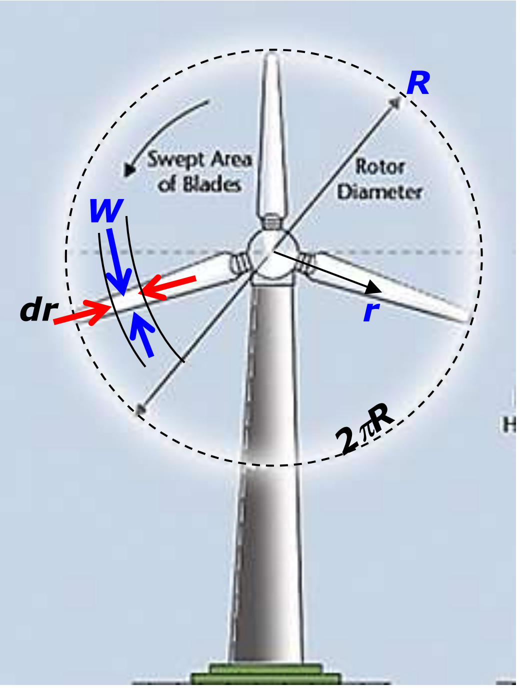
Properties of Wind Energy Turbine Systems[a]

Rated electrical power (kW)	3,600	2,500	2,000	1,500
Rotor diameter (m)	104	100	80	70.5
Rated wind speed (m/s)	14	12.5	15	13
Cut-in wind speed (m/s)	3.5	3.5	4.0	4.0
Cut-out wind speed (m/s)	27	25	25	25
Rotor speed (rpm)	8.5–15.3	—	9–19	12–22
Rated power/area (kW/m^2)	0.424	0.318	3.98	0.384
Rated power coefficient	0.257	0.270	0.196	0.290
Tip speed ratio	3.3–6.0	—	2.5–5.3	3.4–6.2

[a] Data from http://www.gewindenergy.com and http://www.vestas.com.

After: Fay & Golomb, Energy and the Environment, Oxford U. Press, New York, 2012

Technical Summary: Design of Wind Rotor Blades



Technical strain problem: $\text{Bending moment } \vec{M} = \vec{r} \times \vec{F}$

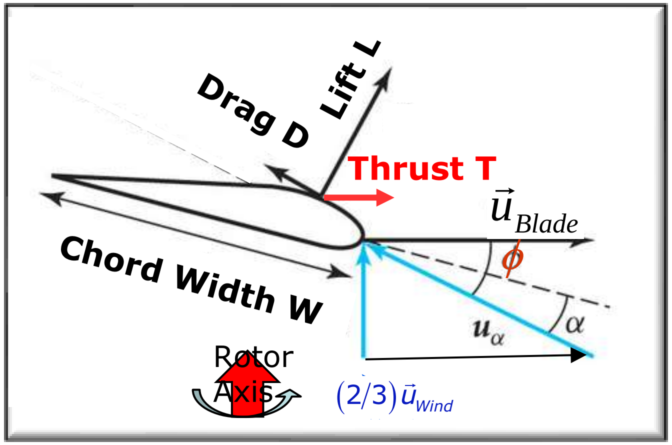
$$\text{"Thrust"} = \text{Force on one blade } T = F = (\rho_m A)\bar{u}^2$$

$$\rightarrow \text{produces desired torque moment on rotor}$$

$$\text{Use mean } \bar{u} = (1-a)u_{Wind} = (2/3)u_{Wind},\ u_{Wake} = (1/3)u_{Wind}$$

$$\text{Per circular strip } dr@r,\quad dT = (\rho_m \cdot 2\pi \cdot r \cdot dr)\cdot \bar{u}^2 \quad \boxed{\triangleq d\vec{p}/dt}$$

To avoid uneven load on blades, reduce camber area *W* and/or angle of attack with increasing *r*.
→ large factor→ stability, normal oscillations



$$\boxed{\text{Wind velocities measured rel. to blades at rest}}$$

$$\boxed{u_{Blade} = u_{Blade}(r) = r\cdot\Omega_{Rotor}}$$

Large range of speeds

Angle of attack α: *wind direction relative to chord*

$$\text{Effective wind speed}\quad u_\alpha = (2/3)u_{Wind}/\sin\phi$$