
WIND POWER

Agenda

Reading Assignments
A&J 4.1-4.4
A&J 6.1-6.13
LN 3.2
Next
A&J 5.1-5.7 (Hydropower)

Resources and Utilization

- Global & local wind resources/patterns

Technology

- Wind tower design and functionality
  - Wind speed distributions
  - Blade aerodynamics, lift and drag, wake turbulence
  - Turbine power generation, design parameters

Technical Summary

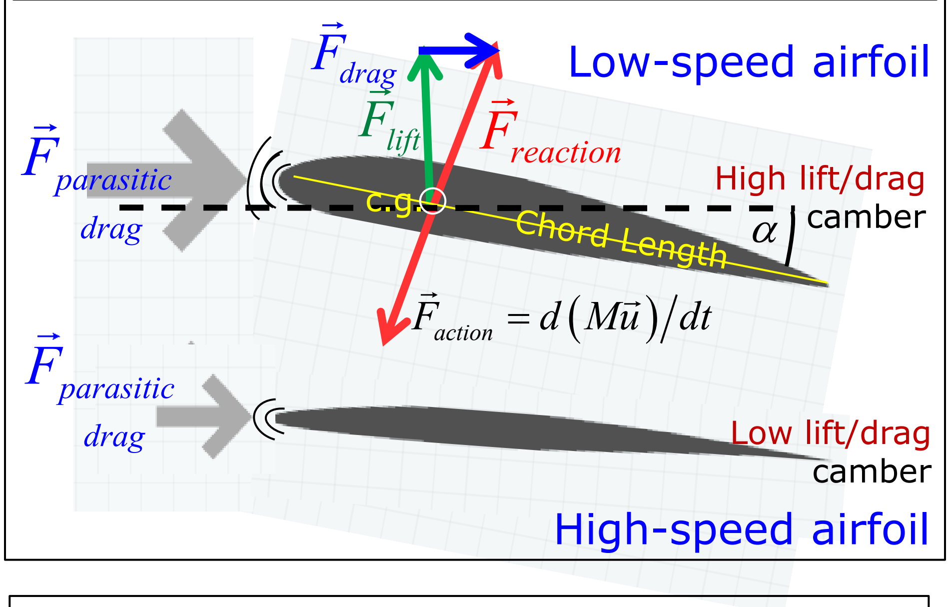
- Wind farms, design and operations
  - Onshore and offshore windfarms, useful life
  - Construction parameters, cost, GHG emissions

Wind power in national energy mix

- Global and U.S. wind power: Status and outlook
  - Installations, prospects for NetZero
- Strategic issues
  - Performance, ecological impact,…

Airstream Deflection by Airfoils

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



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

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

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

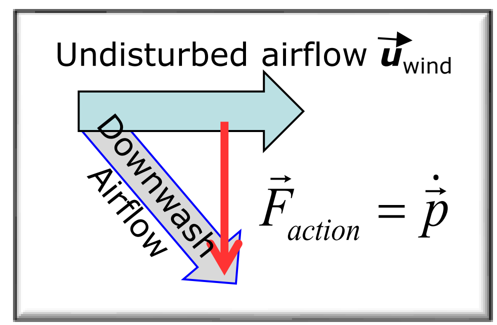
$$\rightarrow \vec{F}_{reaction} = -\vec{F}_{action} = \vec{F}_{lift} + \vec{F}_{drag}$$

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)

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

Low lift camber generates lift at high speeds relative to airmass.

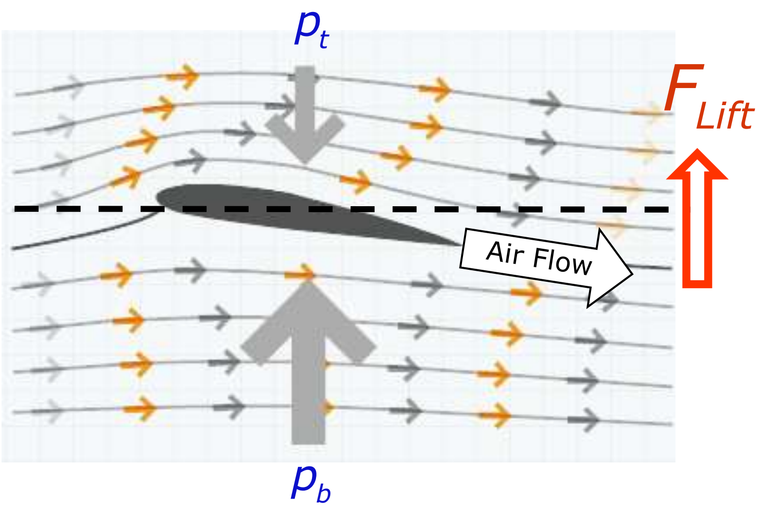


Deflecting airstream→Newton's Law

$$\vec{F}_{action} = -\vec{F}_{reaction}$$

Airstream Pressure Differential by Airfoils

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



Additional (lesser) lift & drag source:

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

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

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

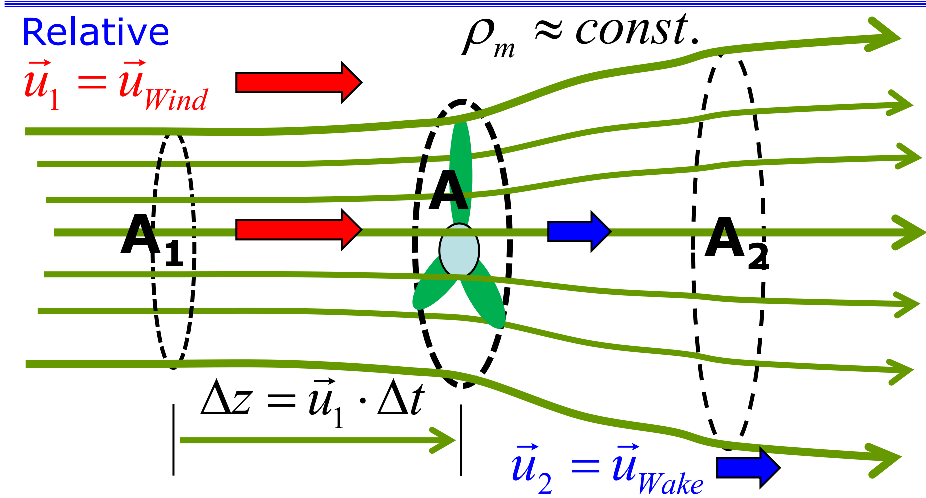
$$F_{Lift} \propto A \cdot \bar{u} \cdot \Delta u(\alpha, \ldots); \quad \Delta u \approx \alpha \cdot \bar{u}$$

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

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.

Aerodynamic Power Transfer



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

$$Traversing\ A: \Delta V(u_1) = (u_1 \Delta t) A$$

$$with \quad \boxed{\Delta E_{kin}(\Delta V) = (\rho \cdot \Delta V) \cdot \frac{m}{2} u_1^2}$$

$$Continuity \rightarrow j_1 A_1 = \rho \cdot u_1 \cdot A_1 \approx \rho \cdot u_2 \cdot A_2 = j_2 A_2;\ mass\ density\ \rho_m = m \cdot \rho$$

$$Power\ flux @ A_i: \boxed{P_i = \frac{\Delta E_{kin}}{\Delta t} = (j_i \cdot A_i) \cdot \left(\frac{m}{2} \cdot u_i^2\right) \propto u_i^3}$$

Power in air flow,
Incoming: *i=1*
Wake: *i=2*

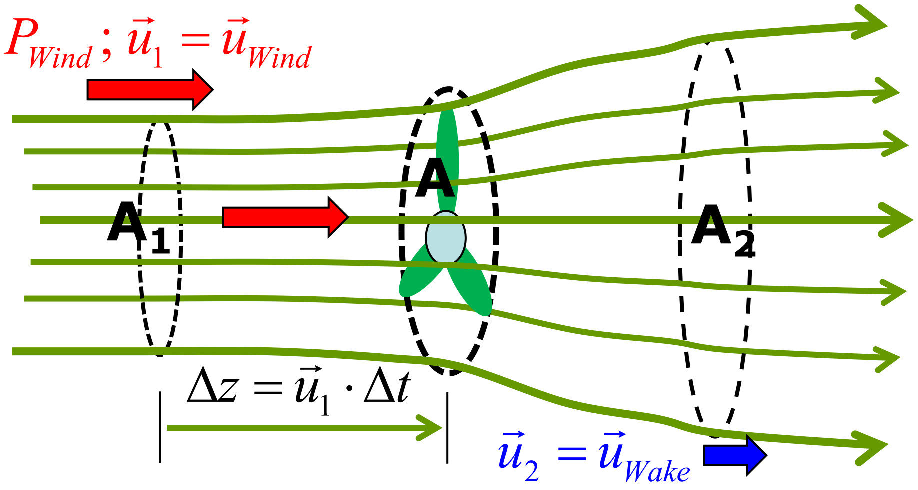
→ Use average speed $\boldsymbol{u_i = \bar{u}}$ *for* mass flow during $\boldsymbol{\Delta t}$

$$Average\ speed\ \bar{u} := (u_1 + u_2)/2\ for\ mass\ flow\ \underline{dM/dt} = \rho_m \cdot \Delta V / \Delta t = \underline{\rho_m \cdot \bar{u} \cdot A}$$

$$\rightarrow Volume\ \Delta V(\bar{u})\ transfers\ power\ differential\ to\ turbine\ \ \bar{j} \approx \rho \cdot \bar{u}$$

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

Aerodynamic Power Transfer



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

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

$$through\ A\ in\ \Delta t: \Delta V(u_1) = A \cdot u_1 \cdot \Delta t$$

$$\Rightarrow \boxed{P_{wind} = \frac{m}{2}(\rho \cdot A) \cdot u_1^3}$$

Delivered to turbine: $\boxed{\Delta P =: C_{Turbine} P_{wind}}$ → *power coefficient* $\boxed{C_{Turbine} = \frac{\Delta P}{P_{wind}}}$

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

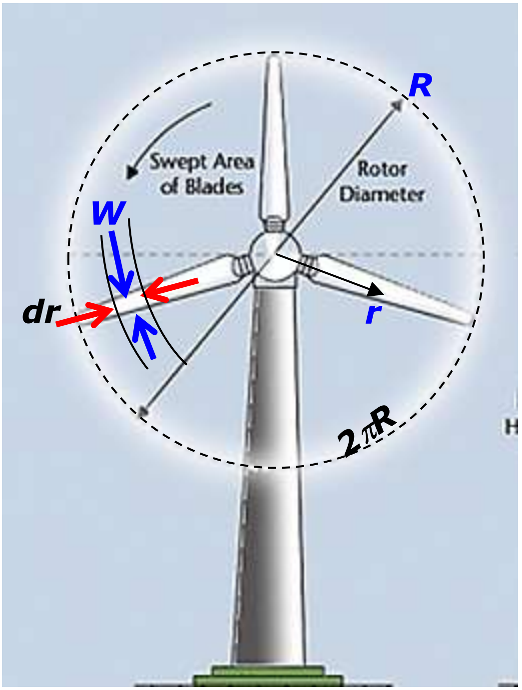
$$Maximum\ power: d(\Delta P)/dx = 0 \rightarrow x\big|_{\Delta P = \max} = 1/3 \rightarrow stable, self\ regulating$$

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

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

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

Turbine Generation Potential & Challenges



Generic analysis of aerodynamic power transfer from *ideal laminar* airmass flows, speed u_{Wind} around turbine with **sweep area** of $A_{TurbineSweep}$

Best performance (@homogeneous conditions):

$$u_{Wake} = \frac{1}{3} u_{Wind} \rightarrow Mean\ \bar{u} = (1-\mathbf{a}) u_{Wind} = \frac{2}{3} u_{Wind}$$

$$P_{Wind} = \frac{\Delta E_{Wind}}{\Delta t} = A_{Turbine\,Sweep} \cdot \left(\frac{\rho_{air}}{2} \cdot u_{Wind}^{3} \right)$$

$$\Delta P_{Turbine} = C_{Turbine} \cdot P_{Wind} \rightarrow 0 \le C_{Turbine} \le \frac{16}{27} = 0.593$$

Betz Limit

Simplistic assumptions: unique camber geometry, relative $\boldsymbol{u}_{\text{wind}}$=const in time and along a blade → mechanical stability: load distribution.

Specific aerodynamic design of rotor blades: with increasing *r*, taper camber area *W* and adjust angle of attack α (twist blades).
Compromise: Efficiency vs. mechanical stability (vibrations)
→ N=3 blades per rotor.
Operational range: Blade tip speed/wind speed $\lambda = u(R)/u_{\text{wind}} \approx$ 3-7.

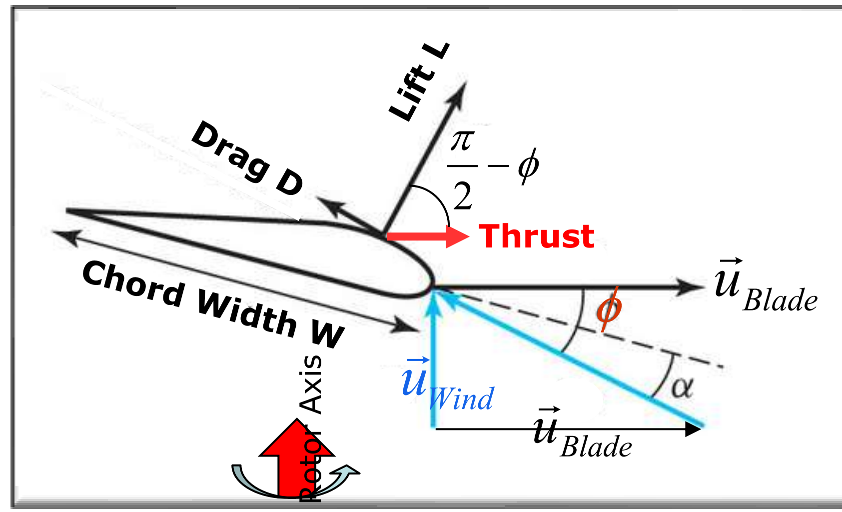
Rotor Blade Aerodynamics

Aerodynamics along blade profile :

1) Lift is low close to hub (root), high at tip.
   Use larger chord close to root.
2) Effective angle of attack decreases with ***r*** → loss of lift @v =const. efficiency.
   Twist blade by 10^0 -20^0 from root to tip.
3) Blade shape adjusted to fit hub & nacelle.

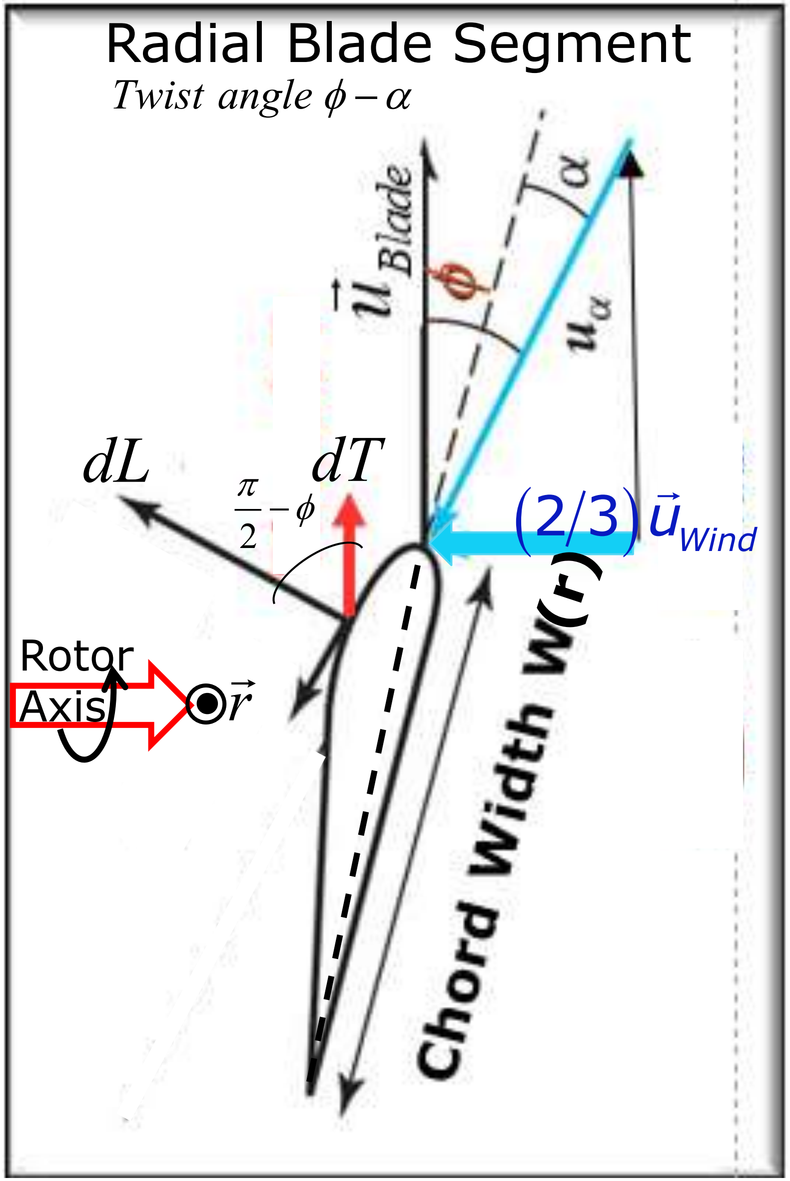
Wind relative to moving rotor blade

$$\vec{u}_{relative} = \vec{u}_{Wind} - \vec{u}_{Blade}$$



Velocity $u_{Blade} - r\cdot\omega$ of blade relative to air increases with radial distance ***r*** from hub → lift increases with ***r*** for a given angle of attack → mechanical strain.
→ Design twist angle $\phi = \phi(r)$

Apparent Wind Velocity Vector



What counts is the relative wind speed and direction.

$$\vec{u}_\alpha = \vec{u}_{Wind} - \vec{u}_{Blade}$$

Blade velocity changes both, speed and effective angle of attack $\phi \rightarrow \phi = \phi(\boldsymbol{r})$.

$$\tan\phi = \frac{u_{Wind}}{u_{Blade}} \quad and \quad u_{Blade}(r) = \frac{r}{R} u_{Tip}$$

Convenient Approximation

$$\vec{u}_\alpha \rightarrow \vec{u}_\alpha = \frac{2}{3} \frac{\vec{u}_{Wind}}{\sin\phi(r)}; \tan(\phi(r)) = \frac{2}{3} \cdot \frac{R \cdot u_{Wind}}{r \cdot u_{Tip}}$$

Thrust dT on ring segment dA from power dP

$$dP = dT \cdot u_{Blade} = dL \cdot \cos\phi \cdot u_{Wind} = dL \cdot \sin\phi \cdot u_{Blade}$$

$\leftrightarrow$ *thrust dT on element W*

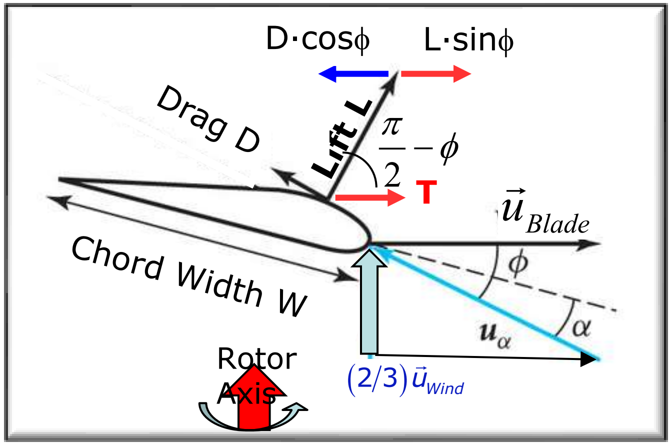
$$dT = dA \cdot \rho_m \cdot \left(\frac{2}{3} u_{Wind}\right)^2$$

circular sweep area

$$dA = 2\pi \cdot r \cdot dr$$

$$dL = \frac{1}{2} C_L \cdot (\rho_m \cdot W(r) dr) \cdot u_\alpha^2(r)$$

(Lift) Induced Drag



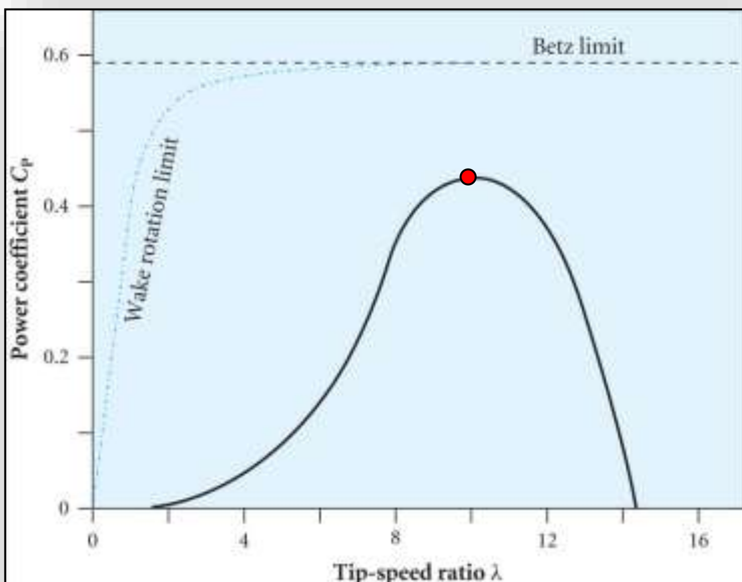
For an air foil exposed to an air flow, there is always an induced drag associated with lift countering thrust:

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

Effective force (thrust) is ⊥ rotation axis

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

Drag/lift ratio: $g = C_d / C_L$



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

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

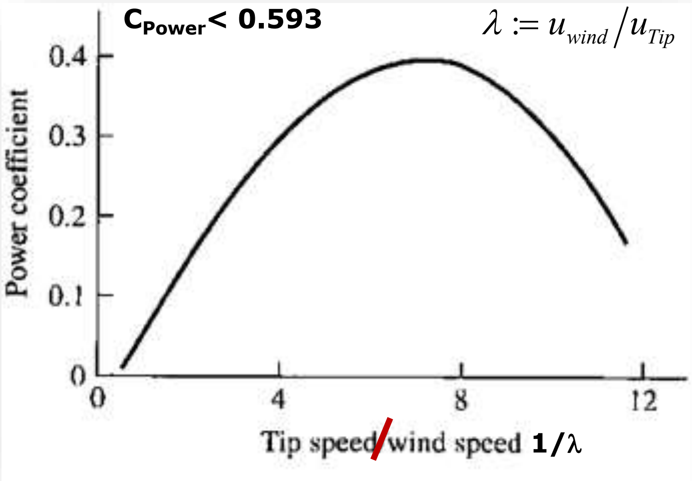
Use typical / representative $r \approx (2/3) \cdot R \rightarrow \cot\phi \approx \lambda$

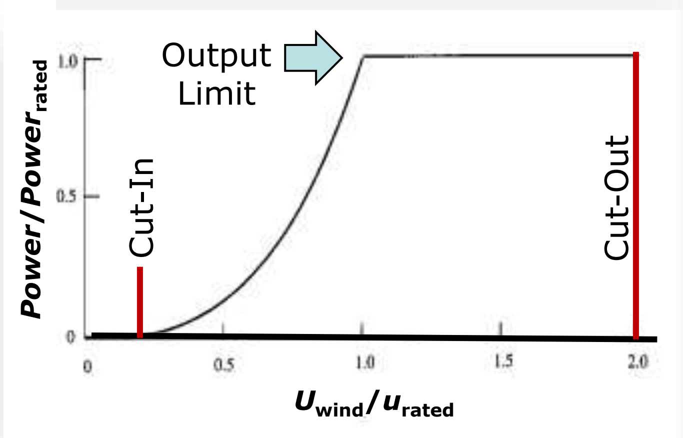
$L_{eff} \sim L \cdot \sin\phi \cdot [1 - g \cdot \lambda] \rightarrow$

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

Modern turbines: g ~ 0.02, λ ~ 10

Operational Turbine Power Limits





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

Operational range of turbines

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

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***:=<Power>$_{time}$/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.

Angular Momentum and Wake Turbulence

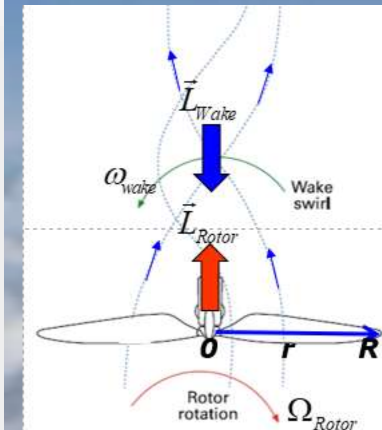


Image Credit: Vattenfall
http://www.noaanews.noaa.gov/stories2011/20110426_windwakes.html

Angular momentum conservation
→ Wake acquires swirl (vortex)

$$0 = \vec{L}_{Wind} = \vec{L}_{Rotor} + \vec{L}_{Wake}$$

Distance between 2 turbines in column $D \geq$ (8-10) rotor diameters

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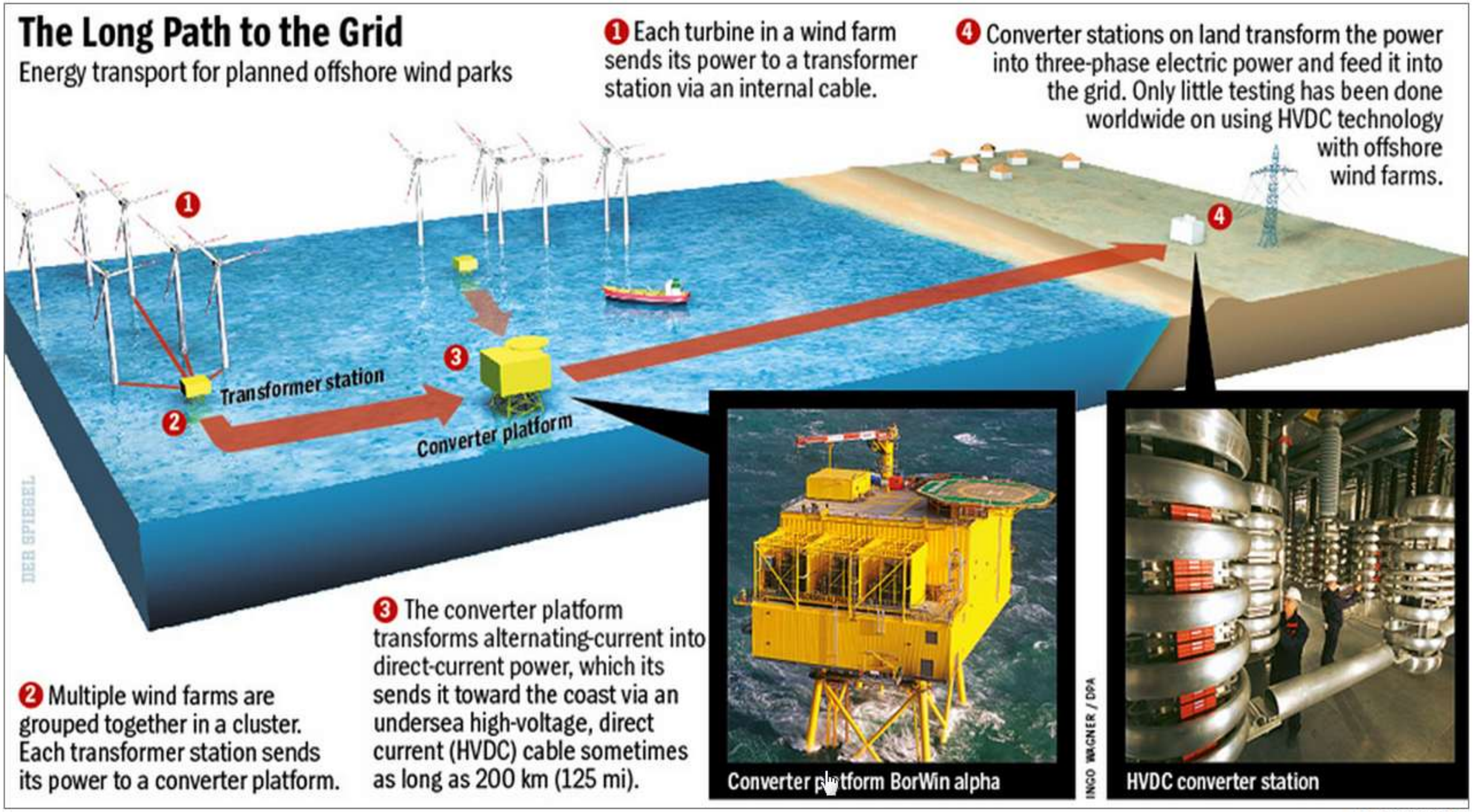
Layout of Wind Farm



Feb 2013 DER SPIEGEL

Germany requires wind farms to be built much further from the coastlines than other countries do, which poses a number of technical challenges. This illustration explains how energy will make its way from wind turbines to the power grid. At the moment, obstacles still remain along this path, and the energy being generated by wind turbines isn't making its way to the grid.

Collector/Inverter Station for Alpha Ventus

To get the power from off-shore wind farms to land, submarine cables (18cm dia, 110 kV HVDC) are used .

Distances are between 10 and 200 km.

Delays in developing technology and manufacturing equipment needed to get the power to shore.

From turbine **30 kV → 110 kV, 75 MVA transformer** (AREVA).
Position: N 54°00', E 6°37.40'
Constructed in September 2008

30 m: elevation of helipad
25 m: elevation of main deck with crane, substation control and protection (I&C)/switch-gear plant/neutral earthing transformer, fire extinguishing system, MV and LV systems, emergency generator,

MVAr throttle / 110 kV GIS (gasinsulated switchgear) system (AREVA)

21 m: cable deck with workshop, equipment room, lounge, diesel tanks, emergency generator, cable bench and oil sump

Cable deck and main deck:
Jacket foundation height: approx. 46 m
Jacket weight: approx. 650 t

Foundation piles: 30 m long, 2.7 m diameter, 100 t apiece

Construction of Alpha Ventus

Fundamente für Offshore-Windkraftanlagen auf dem Gelände der Siag Nordseewerke Emden. Die Stahlstumpen werden, nachdem sie in den Meeresboden gerammt wurden, nur provisorisch beleuchtet. "Mein Schreckensszenario ist, dass da mal ein Schiff reinkracht", sagt der Leiter des Referats Ordnung des Meeres, Christian Dahlke.

North Sea, depth= 30 m, 45km north of Borkum/Germany.

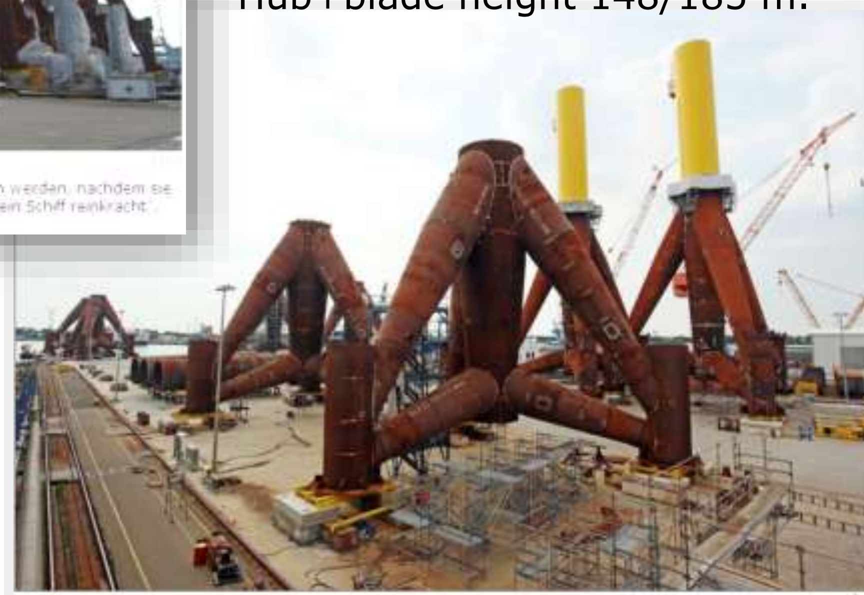
EWE AG, E.ON Climate & Renewables, and Vattenfall Europe Windkraft.

Tripods/towers (45m, 700 t steel) for mounting (12) off-shore AREVA/REpower wind turbines.

Hub+blade height 148/185 m.

Installation of 12 towers=7 months (2009).
Limited number of specialized barges.

Weight of 1 tower: 1,000 t
Tip speed (rated) 320 km/h



Offshore-Windenergieanlagen im Industriehafen in Emden: Sie sollen auf See gebracht werden.

Installing Tower Foundations

DPA/ EWE Energie

Die Gründungspfähle werden im Gebiet 15 Kilometer nordwestlich von Borkum in den Meeresboden gerammt. Das Bundesamt für Seeschifffahrt und Hydrographie warnt nun vor der wachsenden Zahl halbfertiger Offshore-Windparks in der Nordsee.

Construction of Alpha Ventus

REpower Systems/OBS

Installation auf hoher See: Eine Anlage, die speziell für den Einsatz in großen Wassertiefen konzipiert ist, wird aufgebaut.

Construction of Alpha Ventus

In the wake of the 2011 Fukushima nuclear disaster, Gremany announced an energy revolutions, which aims to boost renewable energy to 35 percent of total power consumption in Germany by 2020 and 80 percent by 2050 while phasing out all of Germany's nuclear power reactors by 2022. Plans call for having offshore wind farms play a massive role in this effort.

AREVA Wind Towers for Alpha Ventus

12 turbines @ 5 MW rated,
produced 265 MWh in 2011.

Rotor diameter: 116 m
Hub height: 90 m

Total height above seabed: 178 m
Total above sea surface: 148 m

Rated output: 5 MW
Rotation speed: 5.9 - 14.8 rpm

Cut-in wind speed: 3.5 m/s (force 3)
Rated speed: 12.5 m/s (force 6)
Cut-out speed: 25 m/s (force 10)

Blade tip speed: 90 m/s (324 km/h)

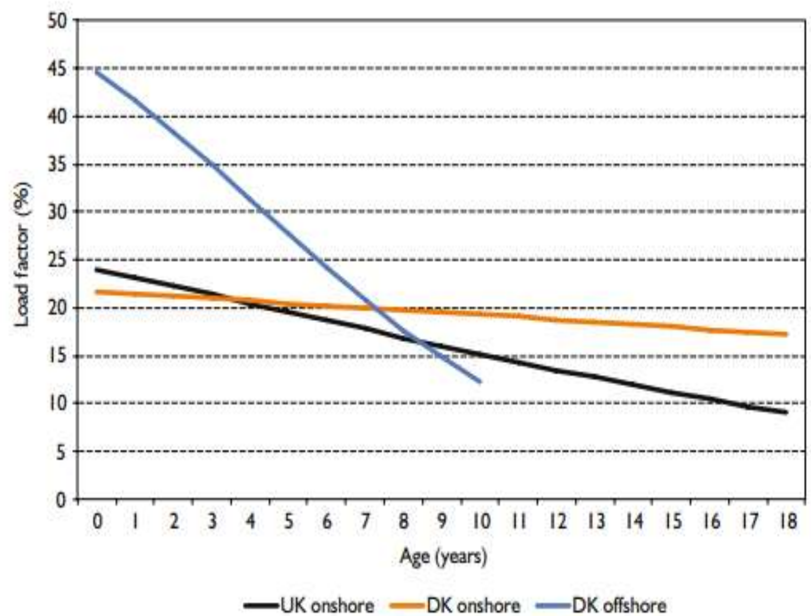
Nacelle w/o rotor & hub: 200 t
with rotor and hub: 309 t

Weight of steel in tripod, tower, nacelle: 1,000 t

Tripod - weight of steel: 700 t;

Height: 45 m; Pile length: 35-45 m

Windfarms: Useful Lifetime



From: Gordon Hughes, The Performance of Wind Farms in the United Kingdom and Denmark

Limited experience from US, Danish and German wind farms.

Onshore wind farms have low-capacity factors but also low maintenance & operational costs and long (30+ year) useful life expectancy.

Off-shore wind farms have higher capacity factors but high operational costs, limited useful life expectancy, due to harsh environment.

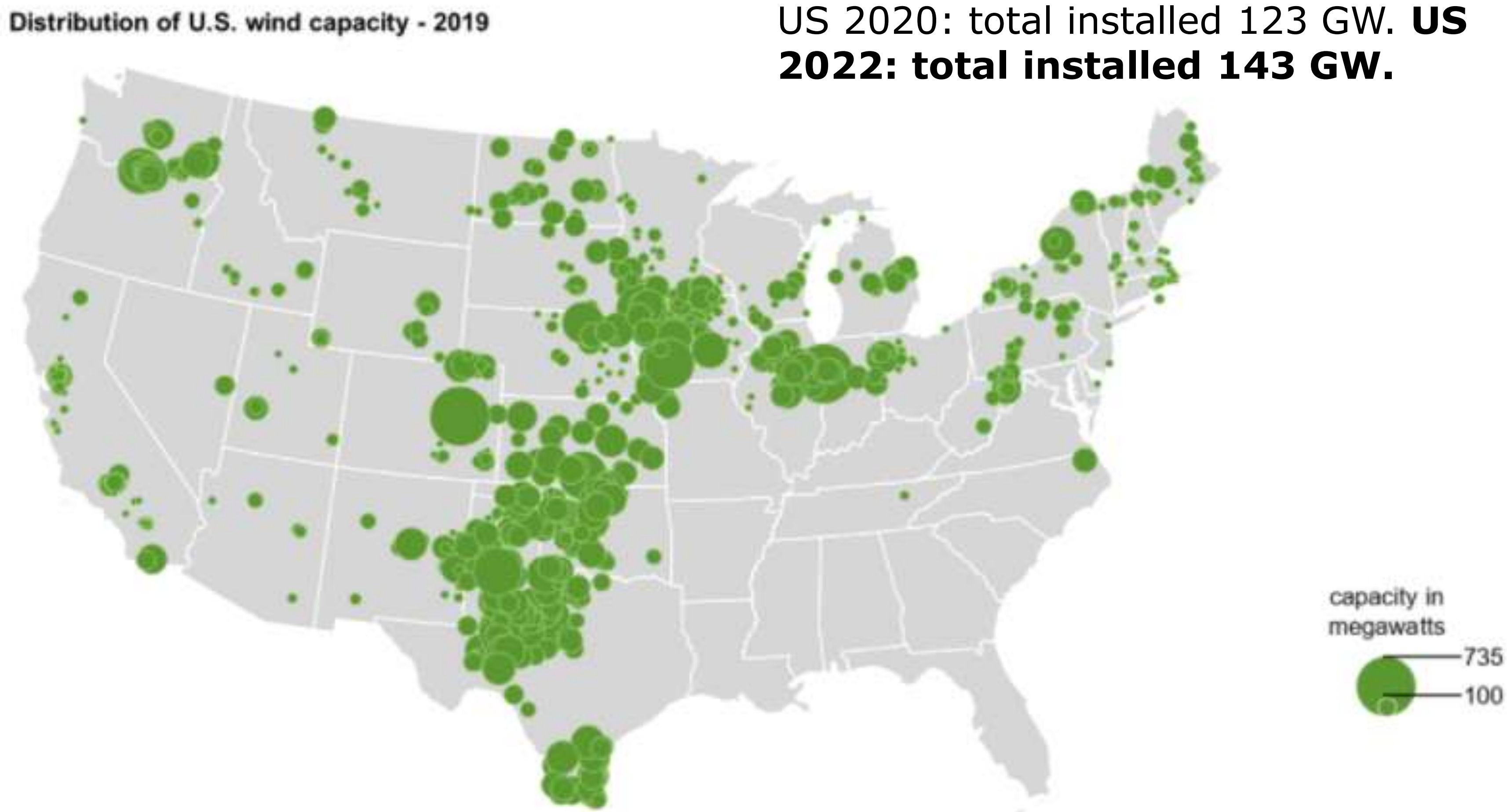
Early Danish experiences with off-shore wind farms: 80 turbines needed replacement in one year.

Danish off-shore wind farms

All data is to the end of Dec 2012	2012 capacity factor	Life capacity factor	Age (y)	MW_p	Life Total elec. gen. (GWh)
Avedøre Holme	**40.1%**	38.0%	2.5	10.8	90
Nysted (Rødsand) II	**45.9%**	44.5%	2.5	207	2053
Sprogo	**36.4%**	35.6%	3.2	21	208
Horns Rev II	**52.0%**	48.4%	3.3	209.3	2959
Nysted (Rødsand) I	**39.5%**	36.8%	9.5	165.6	5097
Frederikshavn	**30.8%**	29.8%	9.6	7.6	191
Samsø	**42.2%**	39.5%	9.9	23	787
Rønland I	**48.5%**	44.6%	10.0	17.2	671
Horns Rev I	**48.1%**	41.2%	10.2	160	5877
Middelgrunden	**25.8%**	25.6%	12.0	40	1078
Tunø Knob	**32.6%**	29.9%	17.6	5	231
Vindeby	**20.2%**	23.5%	21.3	4.95	217
Total	***44.9%***	***39.1%***		***871***	***19,457***

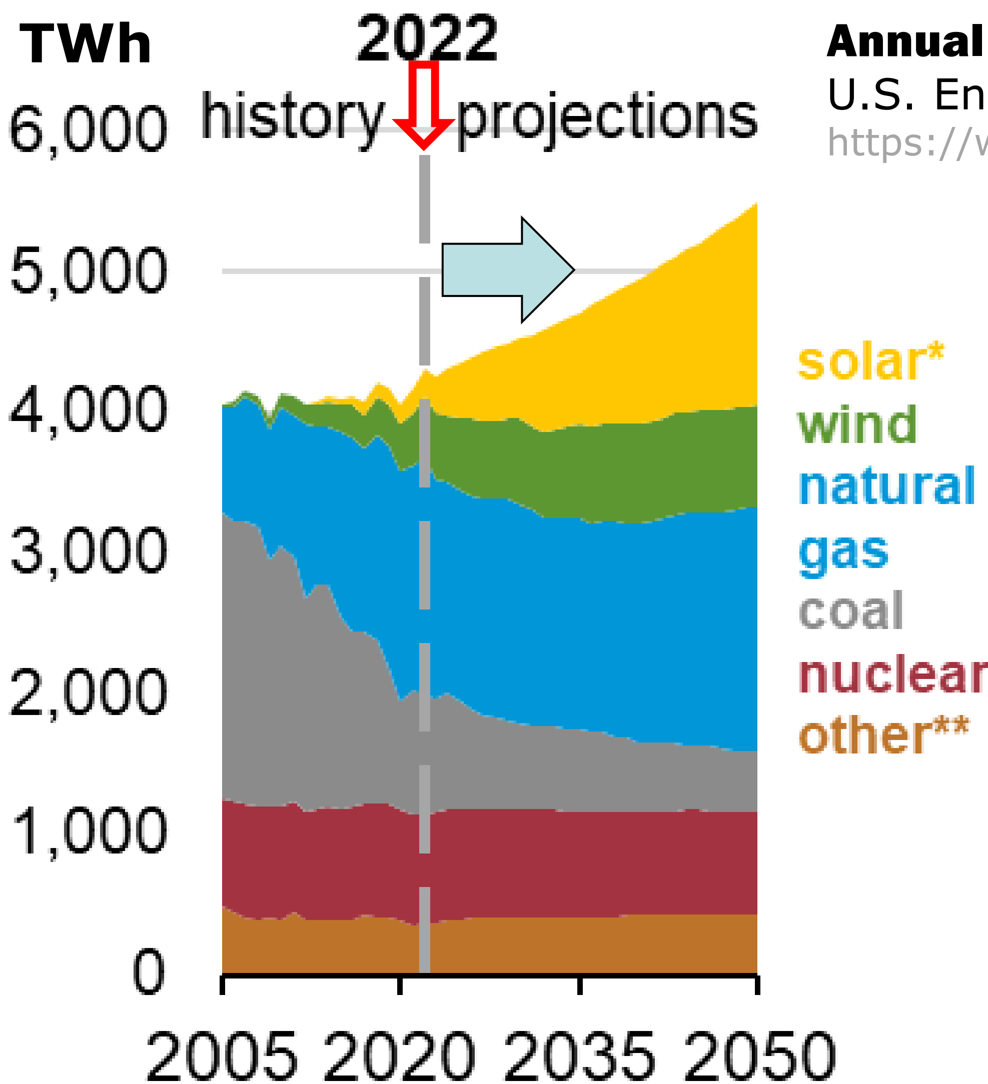
U.S. Electrical Power Plants (Wind)

High rate of installations 2011-2020,
Recent global slow-down.
US 2020: total installed 123 GW. **US 2022: total installed 143 GW.**



Source: U.S. Energy Information Administration, *Annual Electric Generator Report*

Annual U.S. Electricity Production



Annual Energy Outlook **AEO2024**
U.S. Energy Information Administration
https://www.eia.gov/electricity/data/browser/

US 2024 GWh	Source
453.5E+03	Wind
219.8E+03	Solar
242.9E+03	Hydroelectric
781.9E+03	Nuclear
1,869.9E+03	Nat. Gas
652.2E+03	Coal
3,771.2E+03	**Total**

Wind Power: Strategic Issues

- Intermittency, lacking effective energy storage @scale, $CF \approx 0.3$.
  Mis-matched to demand & e-grids, over and under production.
  Need continuous idle backup (baseload) power (> 100% nominal).

- Scalability: Low power density of wind energy resources, ≈3W/m^2→ eco footprint ~(10^2 -10^3)km^2/GW soil/arable land.

- Environmental effects: Habitat degradation/destruction. Visual & audio pollution (stroboscopic flicker, audio effects), ice throw. Endangering/ degrading biomass: bird/bat kill 2-3/(turbine & year). Insects (Germany: Mt/a), relatively unknown habitat effects.

- Efficiency of generation & transmission: operations/maintenance, limited life (<30a). Distance generation-consumption centers, transmission power losses, land for power lines.

- Dependence on critical minerals, metals
  Large amounts of cement/steel, other resources.
- Lack of domestic manufacturing basis for scaling x(5-10) deployment, lack of skilled manpower, special equipment for off-shore.
- Economics: High cost of financing, long time to license & build. Special barges for off-shore installation, expensive maintenance.
- Public attitudes mixed. NIMBY, high power transmission lines.