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

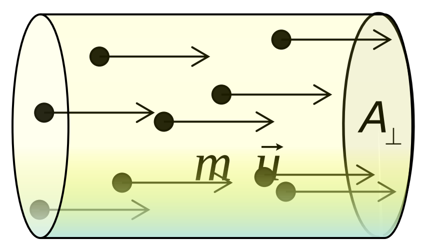
Technical Summary

- 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,…

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

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

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

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

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

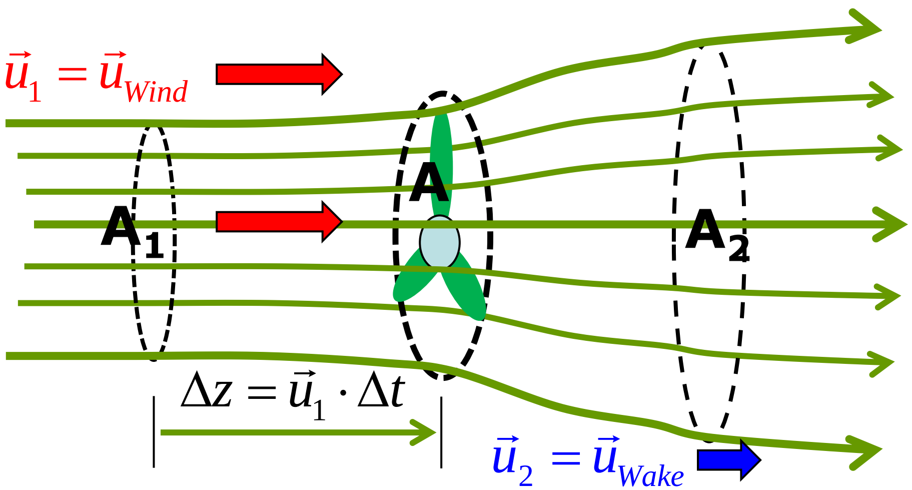
Get force exerted on area A from: $P = F \cdot u \rightarrow F =: F_{drag}$ $\boxed{F_{drag} = A \cdot \left(\frac{\rho_m}{2} \cdot u^2\right)}$

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

$$\boxed{F_{drag} = D = C_d \cdot A_{total} \cdot \left(\frac{\rho_m}{2} \cdot u^2\right)}$$

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

Aerodynamic Power Transfer



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

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

volume ΔV *moves through* A *in* Δt:

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

$$\text{Power flux} \perp A: \quad \boxed{P_i = \frac{\Delta E_{kin}}{\Delta t} = \frac{1}{2} \cdot \left(\rho_m \cdot A_i \cdot u_i^{3}\right)}$$

Power in wind flow, before: *i=1*

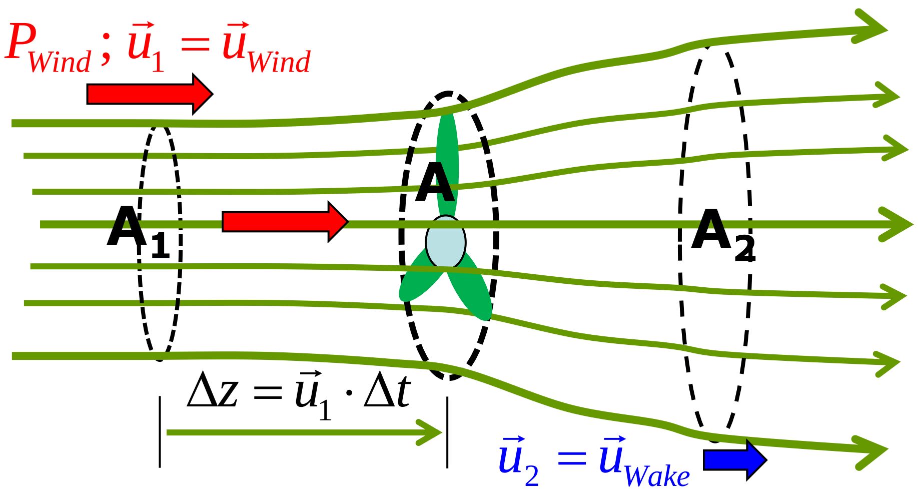
$Continuity: \; j_1 A_1 = \rho A_1 \cdot u_1 \approx \rho A_2 \cdot u_2 = j_2 A_2$ → Use mean *u for* mass flow during Δt

$\rightarrow$ *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, $\mathbf{u_2} = \mathbf{u_{wake}} < \mathbf{u_1} = \mathbf{u_{wind}}$

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

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

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

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

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

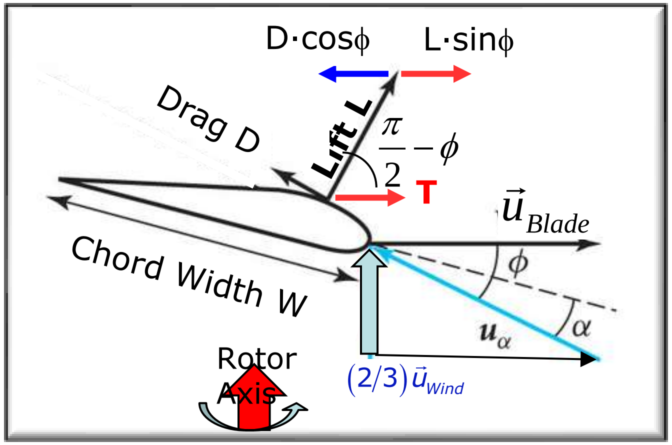
$$Maximum\ \ power: d\left(\Delta P\right)/dx = 0 \rightarrow x\Big|_{\Delta P = \max} = 1/3 \rightarrow self\ \ regulating\ \ stable$$

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

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

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

(Lift) Induced Drag



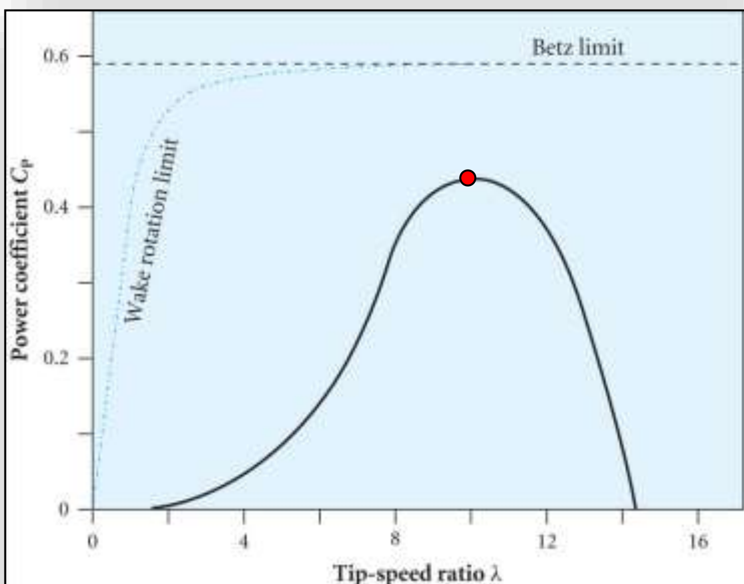
For an air foil exposed to an air flow, there is always an induced drag associated with lift countering thrust:

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

Effective force (thrust) is ⊥ rotation axis

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

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



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

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

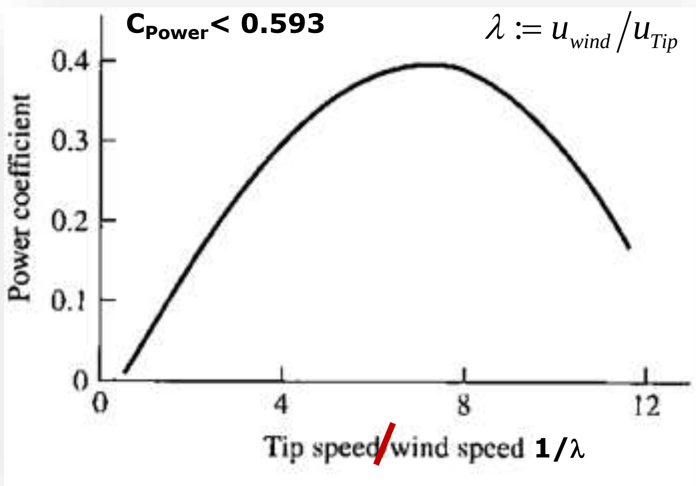
Use typical / representative $r \approx (2/3) \cdot R \rightarrow \cot\phi \approx \lambda$

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

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

Modern turbines: g ~ 0.02, λ ~ 10

Operational Turbine Power Limits



Operational range of turbines

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

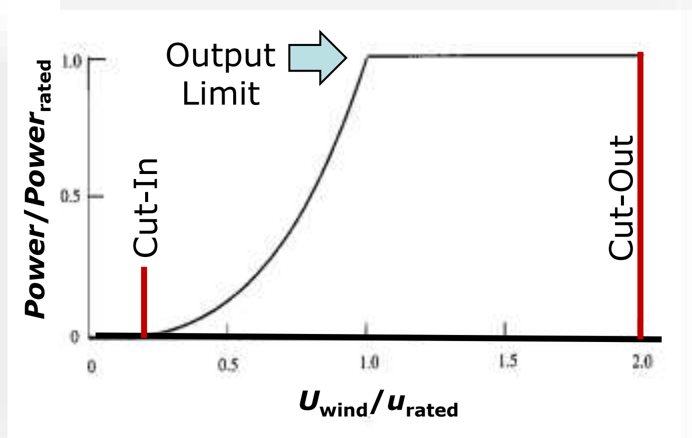
Large range is not economical: electric generator has rotational (power output, frequency) requirements and limitations.

→ 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***$:= \langle Power \rangle_{time}/Power_{rated}$.

Typical: ***CF*** ≈ 0.2-0.4



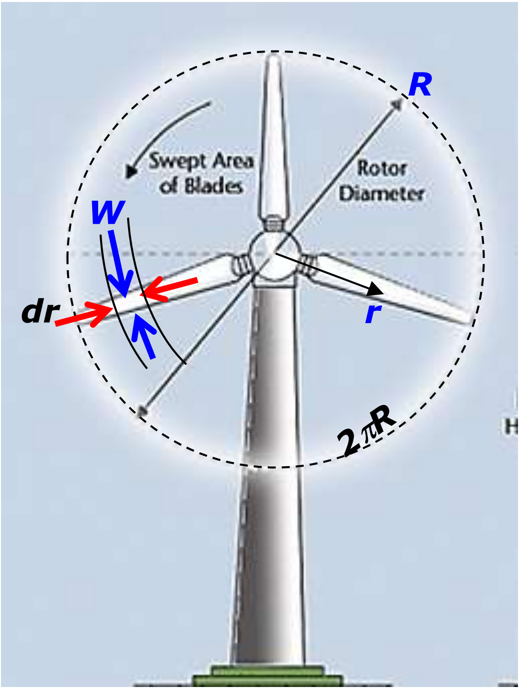
Properties of Wind Energy Turbine Systems[a]

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/m²)	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



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

Best performance:

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

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

$$\Delta P_{Turbine} = C_{Turbine} \cdot P_{Wind} \rightarrow C_{Turbine} \le \frac{16}{27} = 0.593 \quad \text{Betz Limit}$$

$$\rightarrow 0 \le C_{Turbine} \le 0.593$$

Aerodynamic design of rotor blades → with increasing *r*, reduce (taper) camber area W and reduce angle of attack (twist blades).
Compromise: Efficiency vs. mechanical stability → N=3 blades per rotor

Operational range blade tip speed/wind speed λ = 3-7.

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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.

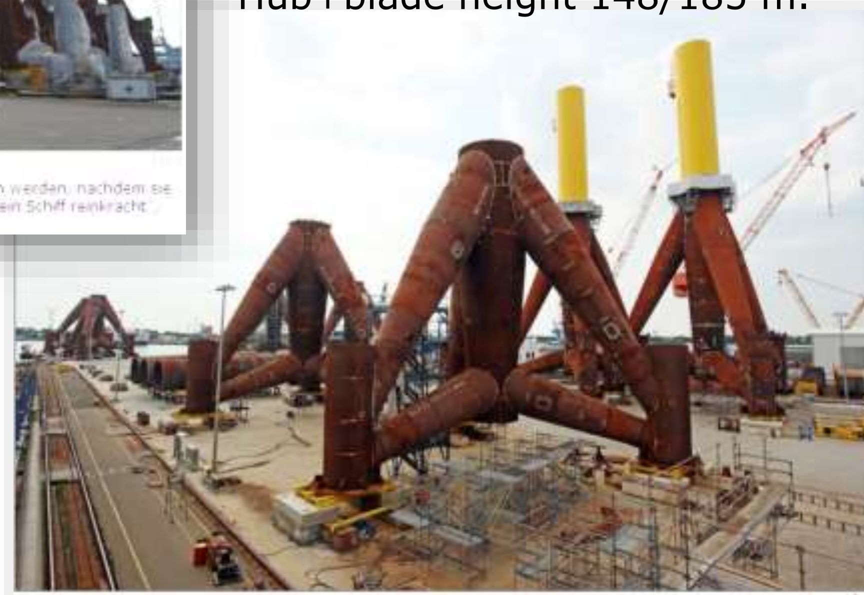
EWE AG, E.ON Climate & Renewables, and Vattenfall Europe Windkraft.

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

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.

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.

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)

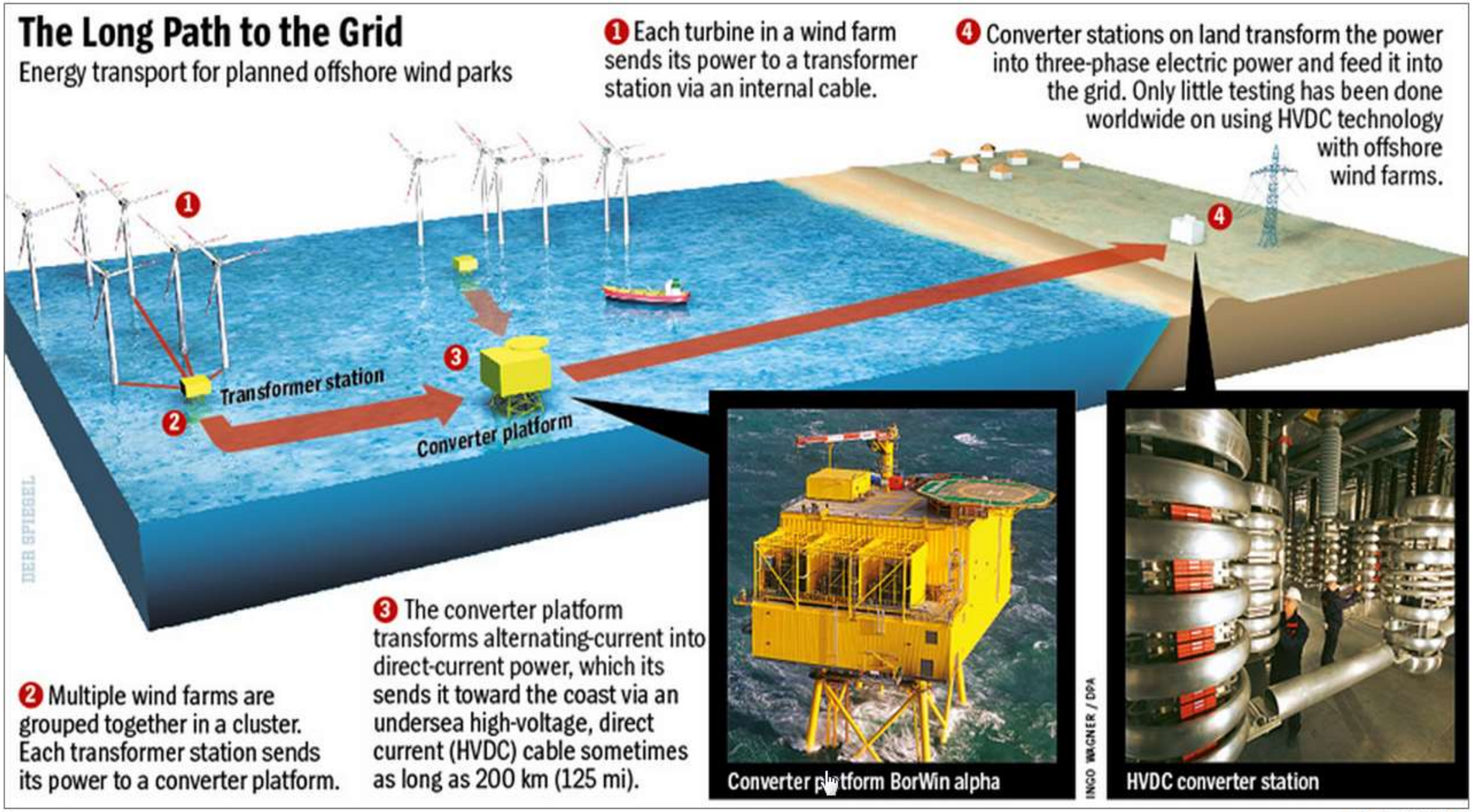
Nacelle w/o rotor & hub: 200 t
with rotor and hub: 309 t

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

Tripod - weight of steel: 700 t;

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

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.

Angular Momentum and Wake Turbulence

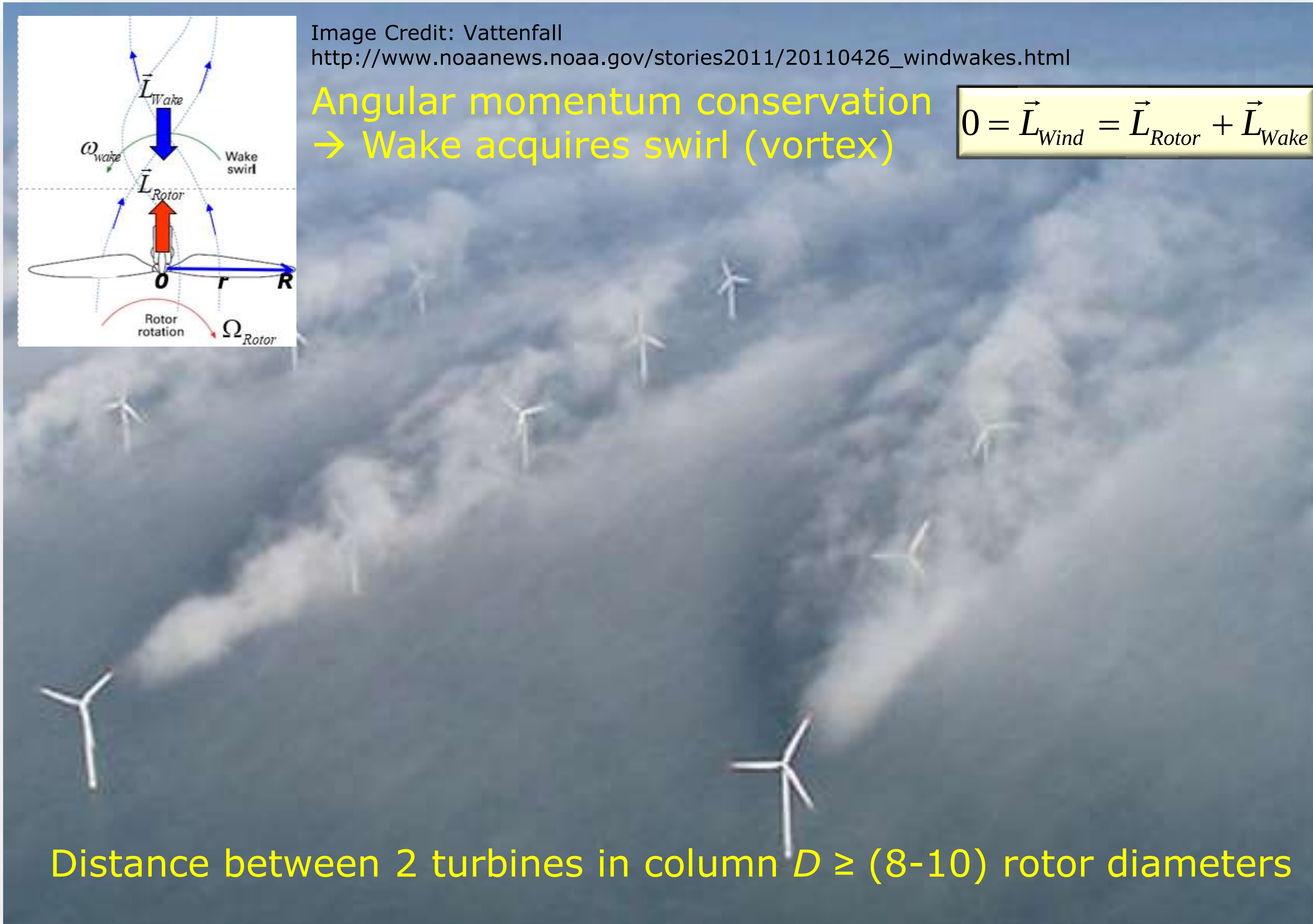


Image Credit: Vattenfall
http://www.noaanews.noaa.gov/stories2011/20110426_windwakes.html

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

Converter 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,

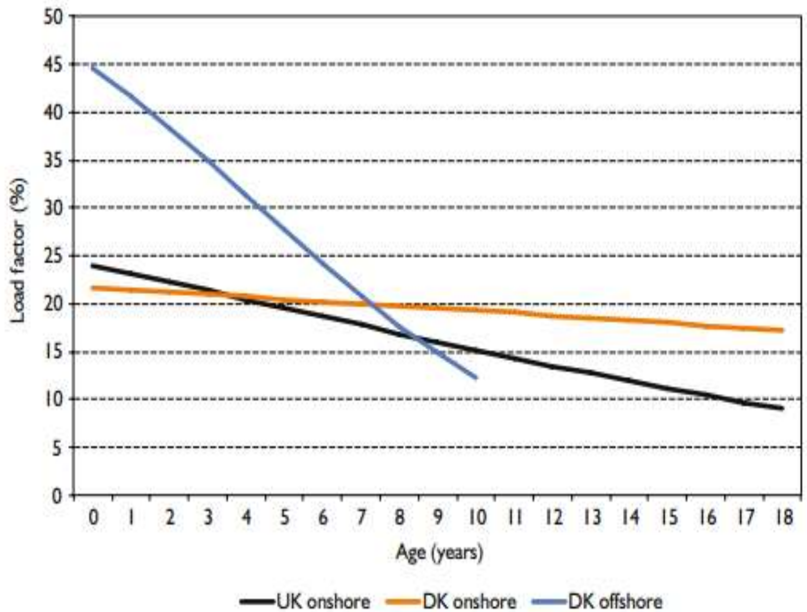
MVAr throttle / 110 kV GIS (gasinsulated switchgear) system (AREVA)

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

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.

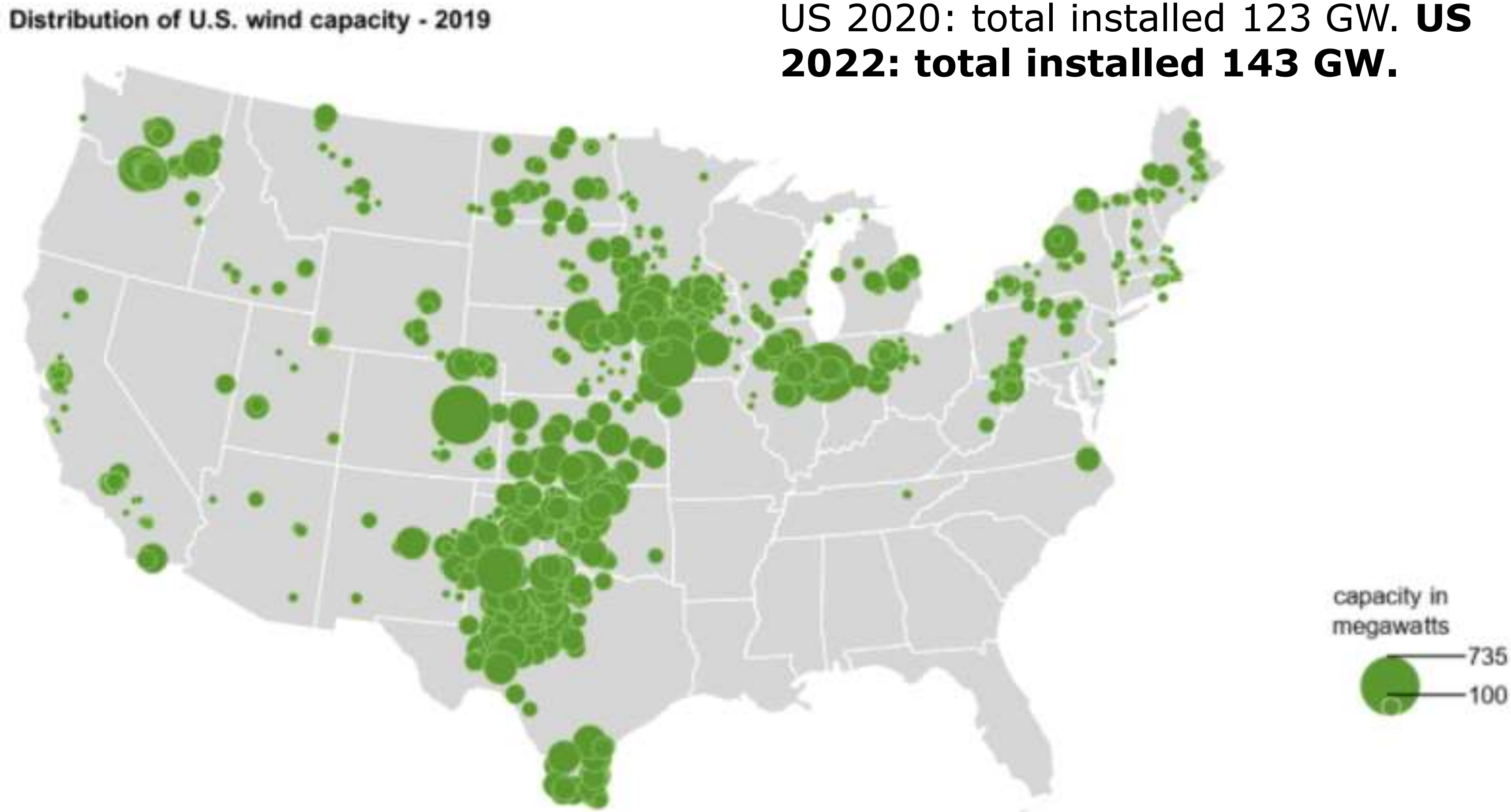
Early Danish experiences with off-shore wind farms: 80 turbines needed replacement in one year.

Danish off-shore wind farms

All data is to the end of Dec 2012	2012 capacity factor	Life capacity factor	Age (y)	MWp	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*

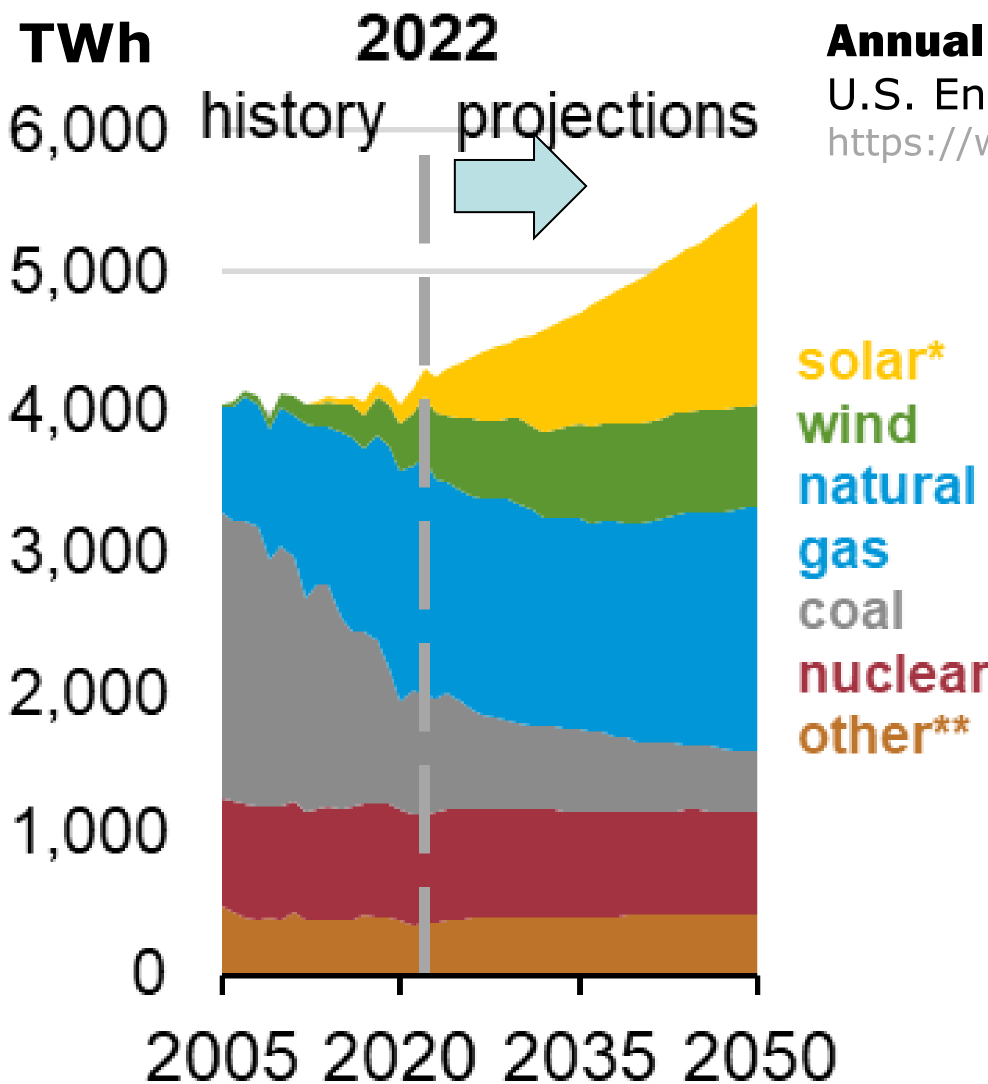
U.S. Electrical Power Plants (Wind)

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

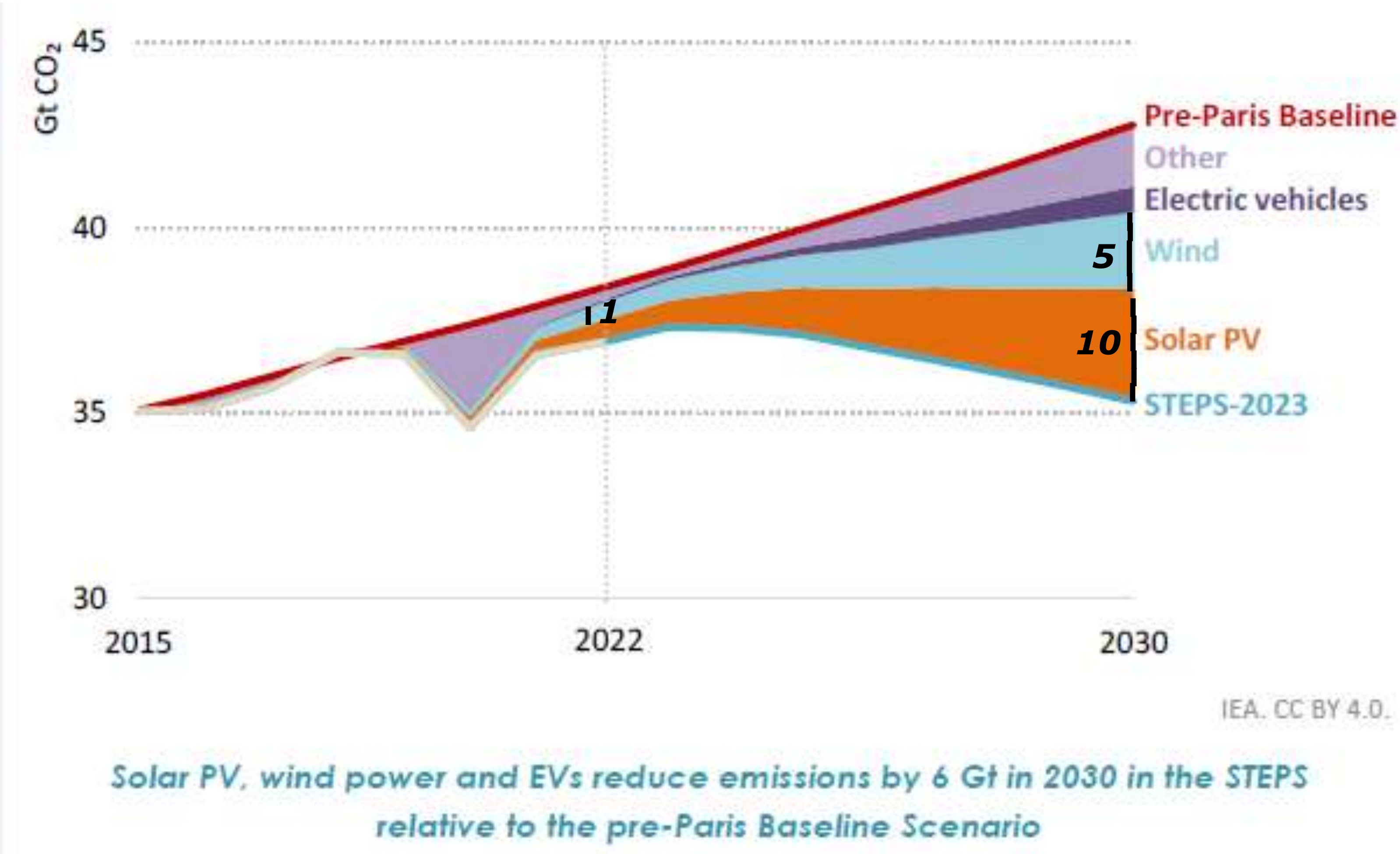


Annual Energy Outlook **AEO2023**
U.S. Energy Information Administration
https://www.eia.gov/electricity/data/browser/

US 2022 GWh	Source
4.21E+05	Wind
2.39E+05	Solar
2.45E+05	Hydroelectric
7.75E+05	Nuclear
1.81E+06	Nat. Gas
6.75E+05	Coal
4.18E+06	**All**

Clean Energy Potential For Decarbonization

DOE: US wind settles at 7%; 2021-2030: +3GW/a; 2031-2050: +8GW/a



Stated Energy Policy Scenarios (STEPS) provides an outlook based on the latest policy settings, including energy, climate and related industrial policies.

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).

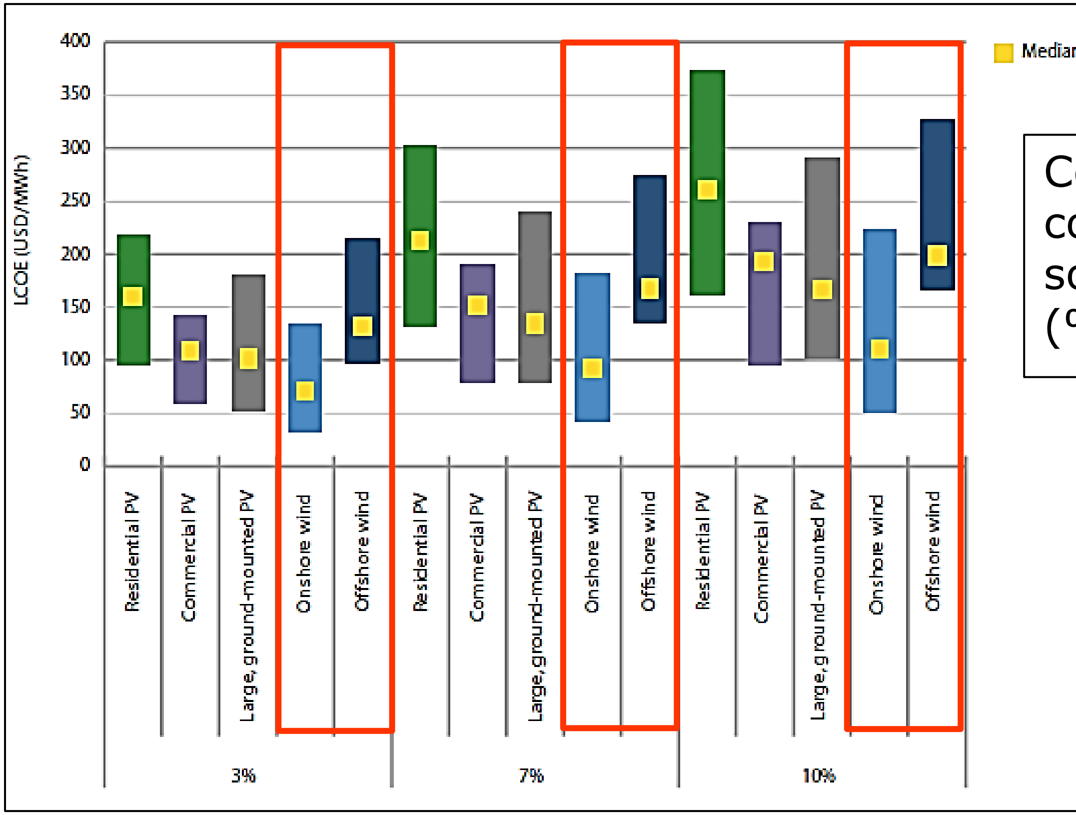
- Scalability: Low power density of wind energy resources, $\approx 3 W/m^2 \rightarrow$ eco footprint $\sim(10^2 - 10^3) km^2/GW$ soil/arable land.

- 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.

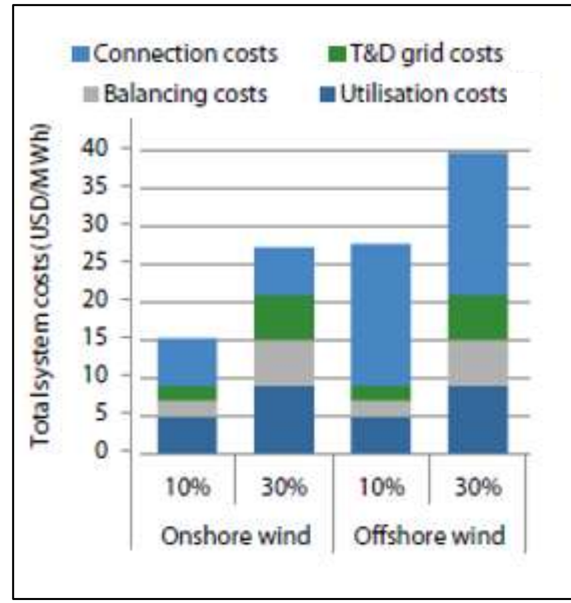
- Efficiency of generation & transmission: operations/maintenance, limited life (<30a). Distance generation-consumption centers, transmission power losses, land for power lines.

- 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.

Wind Energy: Levelized Cost of Electricity



Connection and utilization costs of variable energy sources depend on penetration (%) of total market



Estimates of plant-level costs for renewable power generation technologies at capital costs of 3%, 7% and 10%. (IEA/NEA, 2015, Total cost of energy)

Wind Farm Construction Materials and Emissions

Currently, construction, operation & maintenance of wind farms require non-renewable energy inputs, renewable: fuel=wind, solar.

$$\text{Global warming effect } (MT = \text{metric ton } CO_2 \text{ equivalent}) \quad GWE := \sum_j M_j \cdot GWP_j$$

$$\text{with } M_j = \text{amount of } GHG_j,\ GWP_j = \text{global warming potential for time horizon } (TH = 20 \text{ years})$$

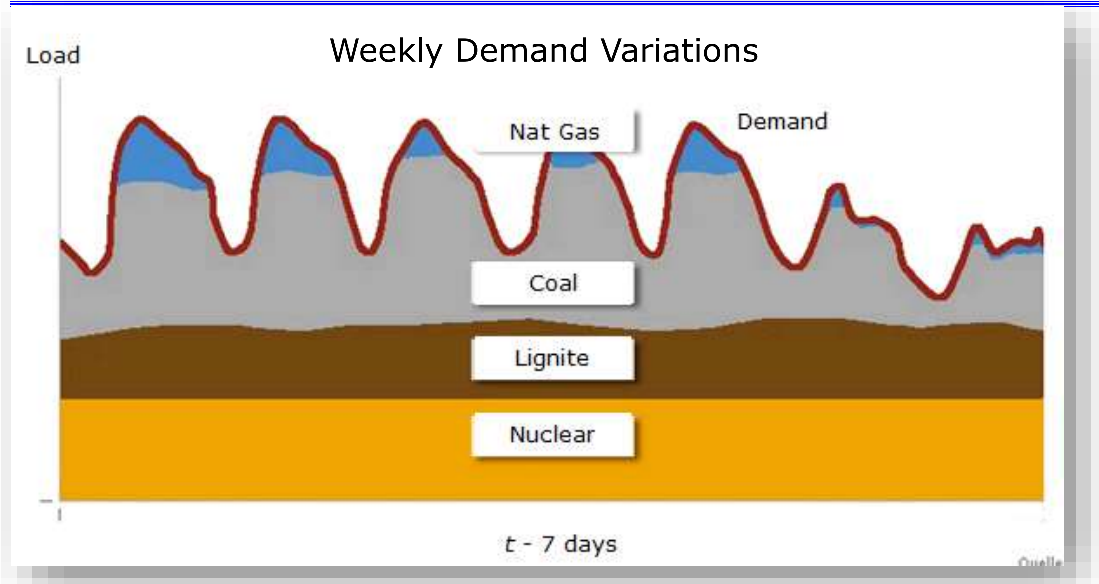
Major Construction Inputs and GWE (after 20 yr) for a Wind Farm[a] 2.7 GW installed

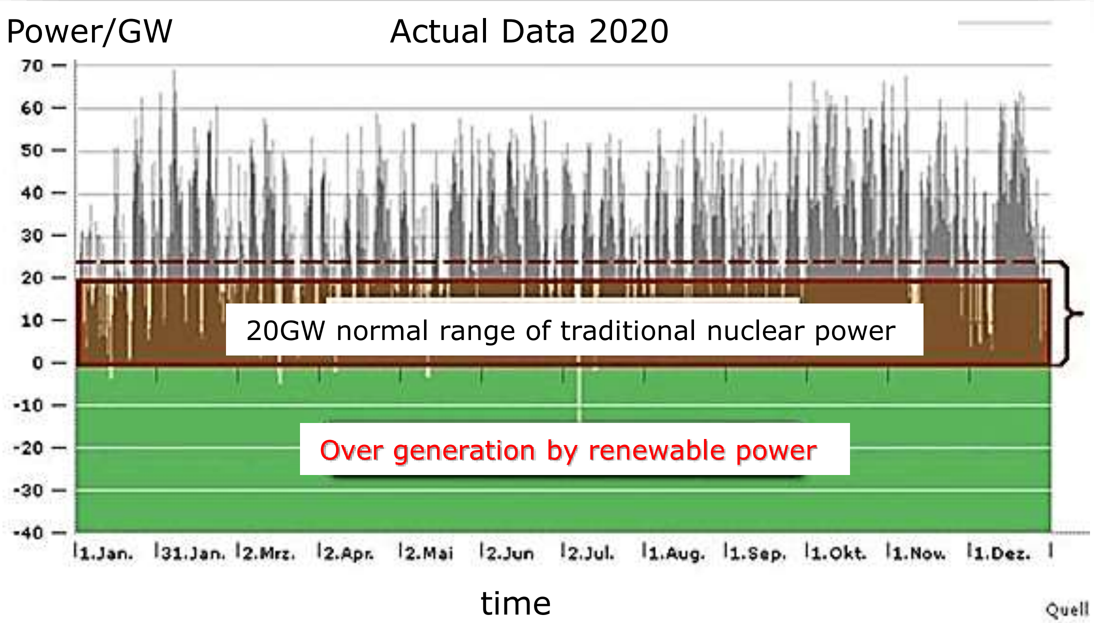
construction inputs	total MT	unit cost (1992 $/MT)	total cost (1992 $)	GHG emissions (MT of CO_2 equiv) CO_2	$+ CH_4$	$+ N_2O$	$= GWE$
steel	289 987	385[b]	111 751 615	426 296	258	2 201	428 755
electricity (MWh)[c]	1 691 678	36[d]	40 756 138	317 231	158	3 008	320 397
concrete	1 266 172	30[e]	37 927 398	51 225	96	1 009	52 330
aluminum	6 275	1 268[b]	7 954 337	14 703	13	225	14 941
plastics	20 169	220[f]	4 445 273	5 090	7	53	5 150
copper	1 569	2 368[b]	3 715 021	3 127	4	33	3 164
glass	4 930	50[b]	246 511	256	0	3	259
oil	448	106[d]	47 380	204	0	1	205
sand	9 412	4[b]	37 743	55	0	0	55
total			206 881 416	800 000	500	7 000	800 000

Cost of only materials. Includes no labor, installation or maintenance costs.

S. Pacca & A. Horvath, Environ. Sci. Technol 36, 3194 (2002)

Electricity Demand and Supply (Example Germany)





2020: 27,000 turbines.

Produced electricity can only partially be fed into grid (over-production→export).

Study by Fraunhofer IWES Institute for Wind Energy and Energy Systems Technologies (Kassel/ Germany). Conclusion for Germany: Present conventional power can partially (40%) be replaced by renewable (wind/solar) production

Power export in EU is limited, except for Denmark (intermediate storage in Norwegian hydro reservoirs)

2023: Nuclear power ramp down.

Wind Farms: Accidents in Perspective

Summary of accidents with more than five fatalities*

(1970-2008)

Energy chain	OECD		EU27		Non-OECD	
	Accidents	Fatalities	Accidents	Fatalities	Accidents	Fatalities
Coal	87	2 259	45	989	2 394[a] 162 818 1 214	38 672 5 788 11 302 15 750
Oil	187	3 495	65	1 243	358	19 516
Natural gas	109	1 258	37	367	78	1 556
Liquefied petro-leum gas	58	1 856	22	571	70	2 789
Hydroelectric	1	14	1	116	9[b] 12	3 961 26 108
Nuclear[c]	–	–	–	–	1	31
Biofuel	–	–	–	–	–	-
Biogas	–	–	–	–	2	18
Geothermal	–	–	–	–	1	21
Wind[d]	54	60	24	24	6	6

* From the Energy-related Severe Accident Database (ENSAD); a) Coal: first line non-OECD total; second line non-OECD without China; third line China 1994-1999; fourth line China 2000-2008; b) Hydro: first line non-OECD without China; second line China; c) Note: Fatalities from the Fukushima Daiichi NPP accident in 2011 are not included in this table, but it should be noted that the accident resulted in no immediate, radiation-related fatalities; d) Wind: only small accidents.

Source: Adapted from Burgherr and Hirschberg, 2014.

→ Wind farms had only minor accidents, few fatalities.

Employment in Renewable Energy Sector

Local jobs in the O&M of various electricity generating technologies, ordered by average size of the electricity generating facility

Technology	Jobs/MW	Average size (MW)	Direct local jobs
Nuclear	0.50	1 000	504
Coal	0.19	1 000	187
Hydro > 500 MW	0.11	1 375	156
Hydro pumped storage	0.10	890	85
Hydro > 20 MW	0.19	450	86
Concentrating solar power	0.47	100	47
Gas combined-cycle (CCGT)	0.05	630	34
Photovoltaic (PV)	1.06	10	11
Micro hydro < 20 MW	0.45	10	5
Wind	0.05	75	4

Source: Harker and Hirschboeck, 2010.

Most local employment is during installation 200MW ➔ 500 workers

Many energy sector jobs are not co-local (engineering, design, financing, transient maintenance).

Non-specific, i.e., management, marketing, personnel can be interchanged.

Political vs economic considerations:
High labor intensity is of interest to local politics, but also constitutes disadvantage in economic competition.

Quality of the labor: higher qualification of the work-force → longer duration of the employment → higher long-term positive externalities.

Wind Related Failures

High-wind rotor failures

Gale winds (~100mph) in England and Scotland in 2012.

Material fatigue after 10 years' operation ?

http://www.dailymail.co.uk/news/article-2083149/Wind-turbines-cope-UK-weather-3-blown-pieces.html

Blade icing if ambient/dew point temperature < (3^0-4^0)C

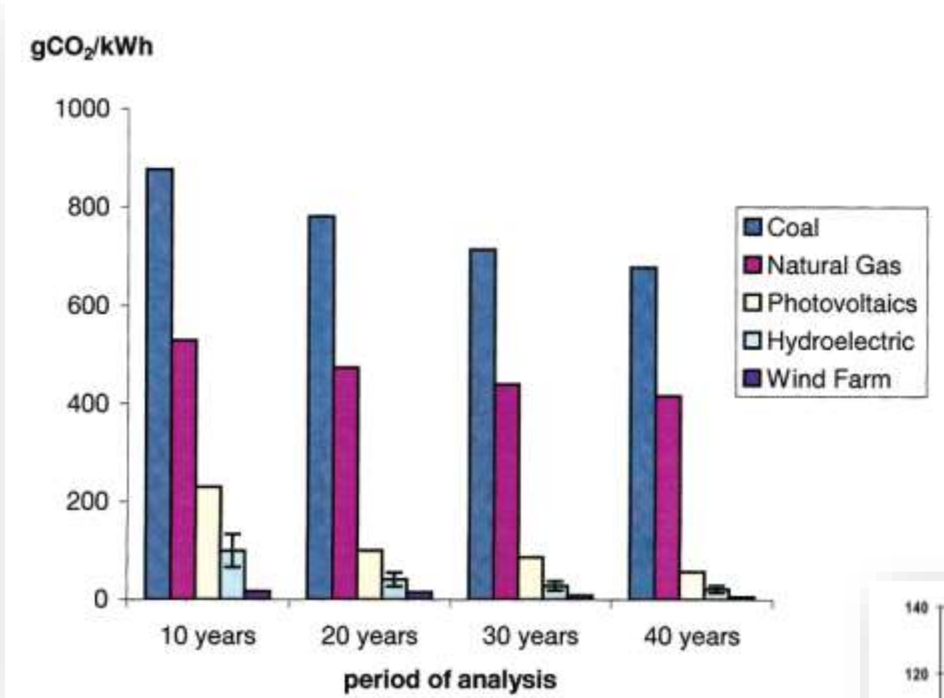
Ice throws due to blade flexing

Effect on Wildlife

[Newsweek:](#)2007 study by the National Academy of Sciences puts the number of birds killed each year at about 20,000 to 30,000. The American Bird Conservancy estimates about 80,000 to 220,000 bird fatalities per annum, due to wind power. Read Birds vs. the Wind Industry.

Relative risk is small (kills by other means), can be reduced further..

Pro/Con: Avoided GHG Emissions @ Price

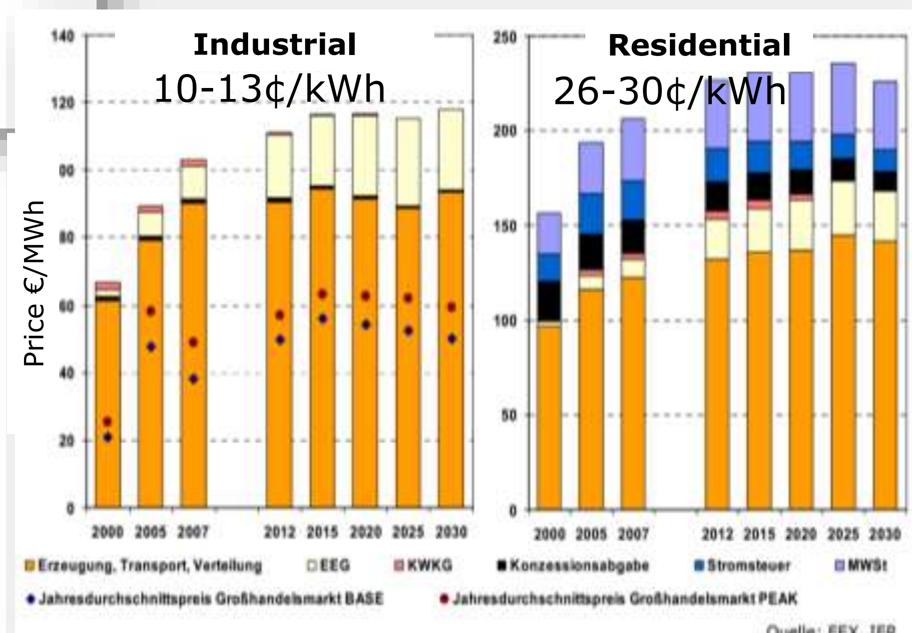


Estimated CO_2 equivalent needed for construction of infrastructure for a 1GW wind farm is $1.2\cdot10^6$ t CO_2. For ***CF***=1.0, GHG emission is lower
than for hydro-electric generation.

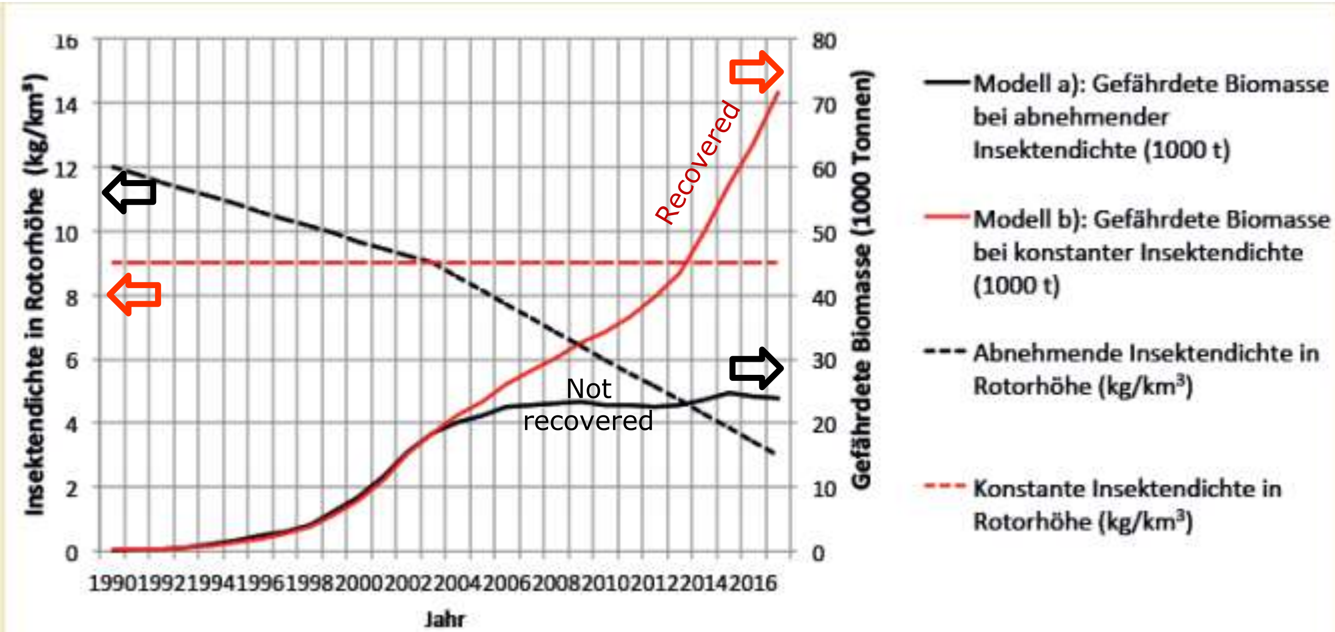
(S. Pacca& A. Horvath, Environ. Sci. Technol. 36, 3194 (2002))

Germany:
electricity price app.=$/MWh

U.S. Residential: 8-15¢/kWh



Effect on Ecosystem: Insect Population



Rotors eliminate 5% of insects flying at rotor altitudes (~ 3kg /km³).Germany: 1,200 Mt/a

Small relative risk? (Birds & other means kill more). Can it be reduced ?

Change of insect density at rotor altitudes → endangered biomass since 1990 in 2 model simulations (Gerz&Geiger, Energiewirt. Tagesfrg. 68, 51 (2018))

Insect fatalities (est.): (5-6)·10^9/day → 1,200 Mt/a (5% of interactions)

Consequences for ecosystem: diminished pollination of plants, effect on crops, elimination of insect biomass from food chain → stresses predator (birds, other animals, insects) population.

Windfarms: Ecological Effects

Tab. 1: Verlauf der installierten Leistung, der Rotorfläche und des saisonalen Luftdurchsatzes durch den deutschen Windpark seit 1990 sowie daraus resultierende Modellberechnungen der gefährdeten und der beschädigten Insektenbiomasse unter der Annahme a) abnehmender Insektendichte und b) gleichbleibender Insektendichte in Rotorhöhe

				a) Abnehmende Insektendichte			b) Konstante Insektendicht		
Jahr	Installierte Leistung	Rotorfläche	Saisonaler Durchsatz	Insekten-dichte	Gefährdete Biomasse	Beschädigte Biomasse	Insekten-dichte	Gefährdete Biomasse	Beschädigte Biomasse
	$P_{windpark}$	A	V_{wind}	δ_{insekt}	M_{Rotor}	$M_{Schaden}$	δ_{insekt}	M_{Rotor}	$M_{Schaden}$
	MW	10^6 km³	10^6 km³	kg/km³	1000 t	1000 t	kg/km³	1000 t	1000 t
1990	63	0,2	0,0	12,00	0,1	0,0	9,00	0,2	0,0
1991	105	0,3	0,0	11,77	0,3	0,0	9,00	0,2	0,0
2010	26.926	75,4	3,8	6,00	22,9	1,1	9,00	34,3	1,7
2011	28.873	80,8	4,1	5,57	22,8	1,1	9,00	36,8	1,8
2012	31.095	87,1	4,4	5,24	22,7	1,1	9,00	39,6	2,0
2013	34.227	95,8	4,8	4,71	22,9	1,1	9,00	43,6	2,2
2014	39.153	109,6	5,5	4,29	23,8	1,2	9,00	49,8	2,5
2015	45.043	126,1	6,4	3,86	24,6	1,2	9,00	57,3	2,9
2016	50.011	140,0	7,1	3,43	24,3	1,2	9,00	63,6	3,2
2017	56.356	157,8	8,0	3,00	24,0	1,2	9,00	71,7	3,6
Kumulierte Biomasse (1990 - 2017)					395	19,8		629	31,4

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Public Acceptance Changed

- Anti windmill demonstration in Erbach (Hesse/Germany) 15.01.2017

WIND POWER