Lecture 7
Wind & Hydro Energies

PHY 555 – Energy & Environment

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Lecture 7 – Wind & Hydro Energies

I. **Hydraulic energy**

II. Wind Resources

III. Betz Limit

IV. Basics of aerodynamics

V. Wind Turbines

VI. Submarine turbines

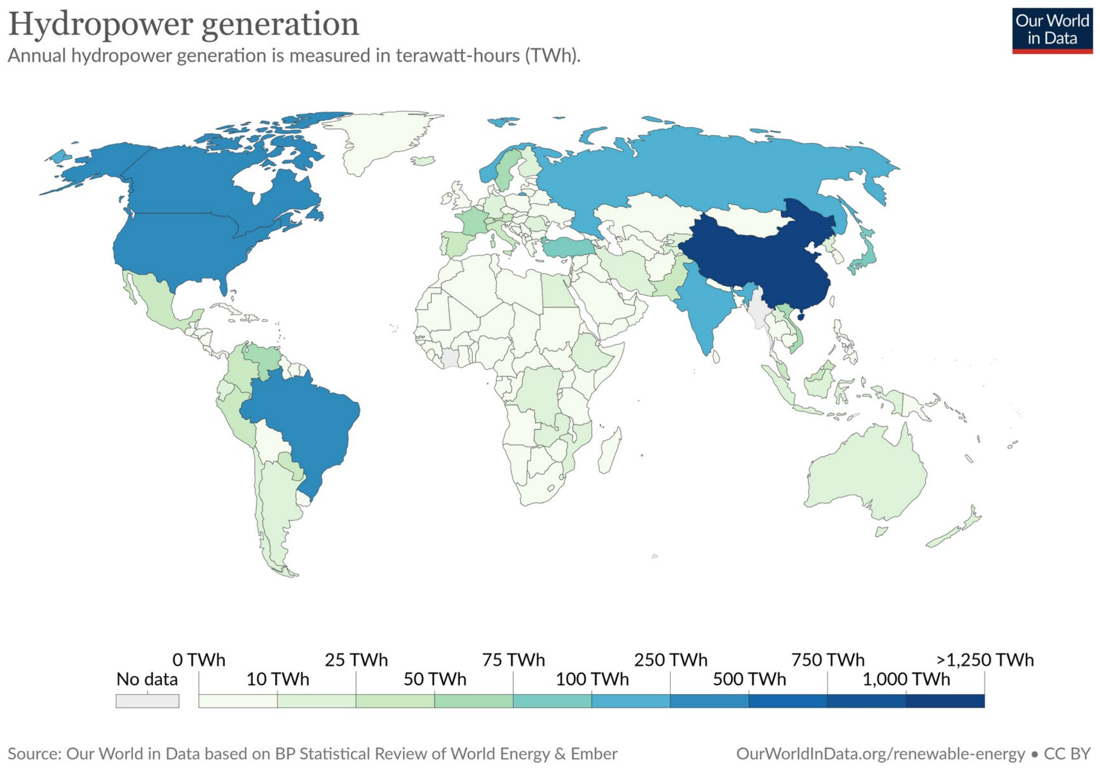
VII. Conclusions & Outlook

Hydraulic energy – Hydropower

- Hydro & Wind are the most ancient sources of renewable energy

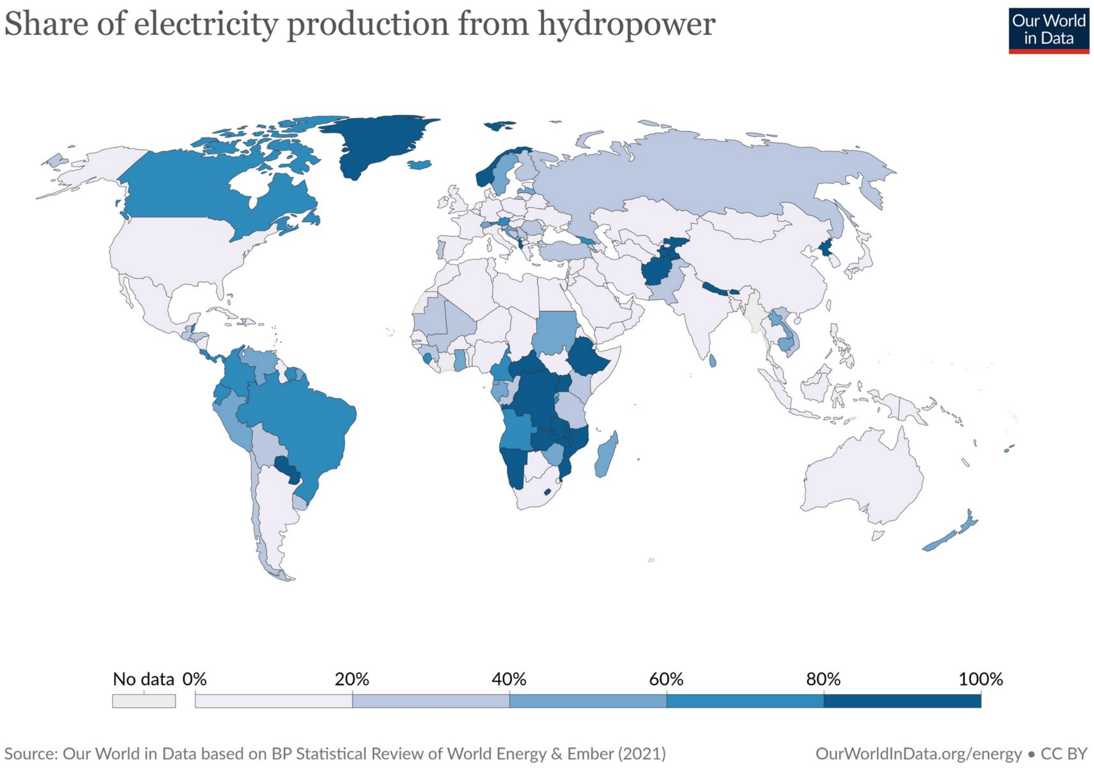
Hydroelectric Power

- Absolute production



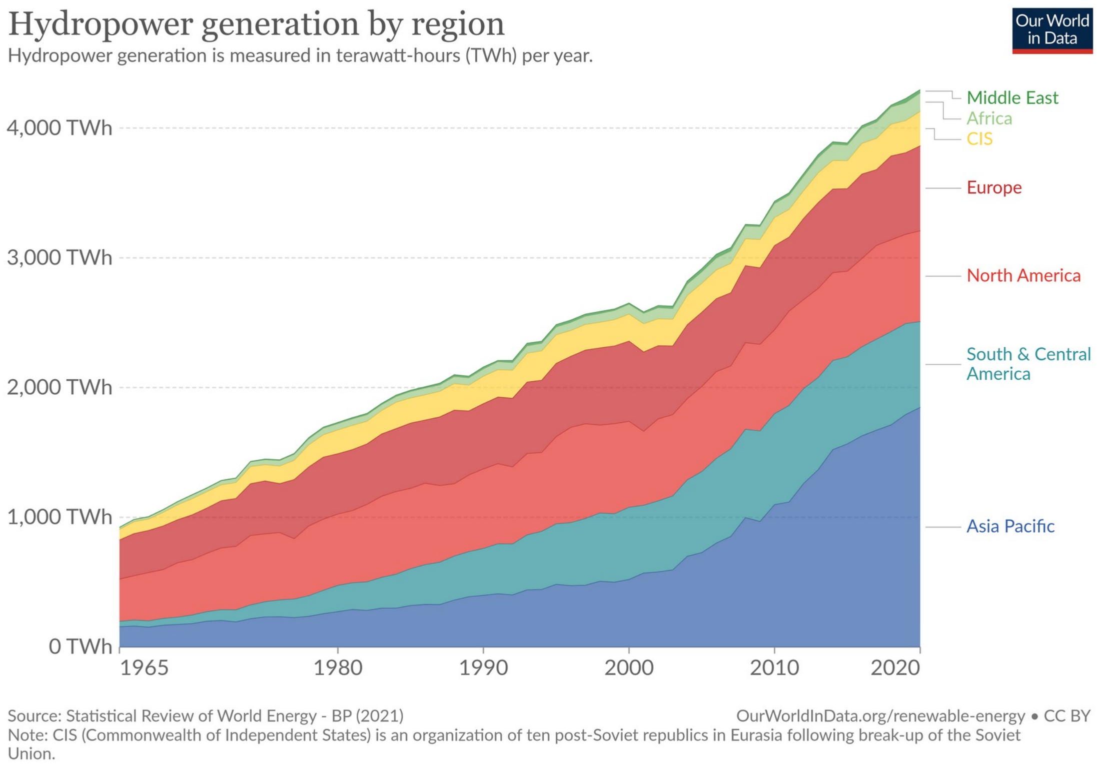
Hydroelectric Power

- Share in electricity mix

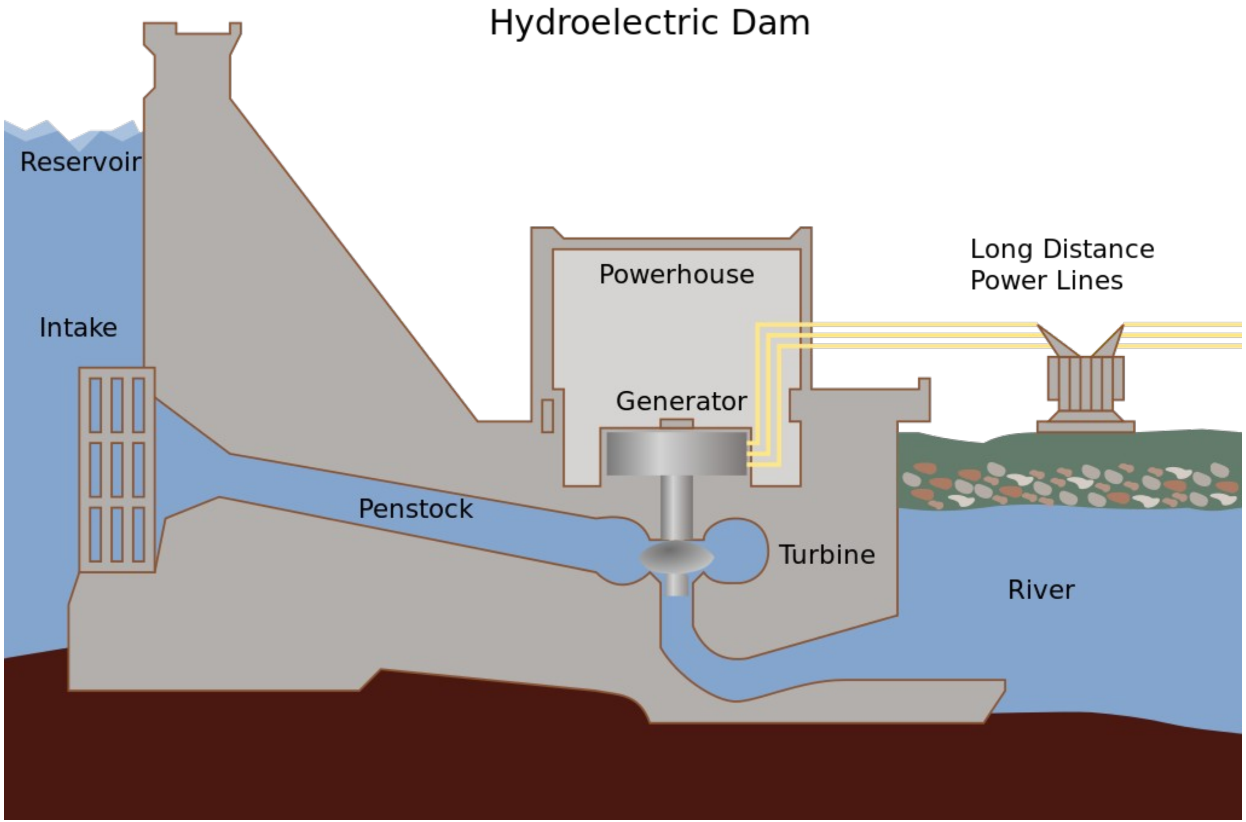


Hydroelectric Power

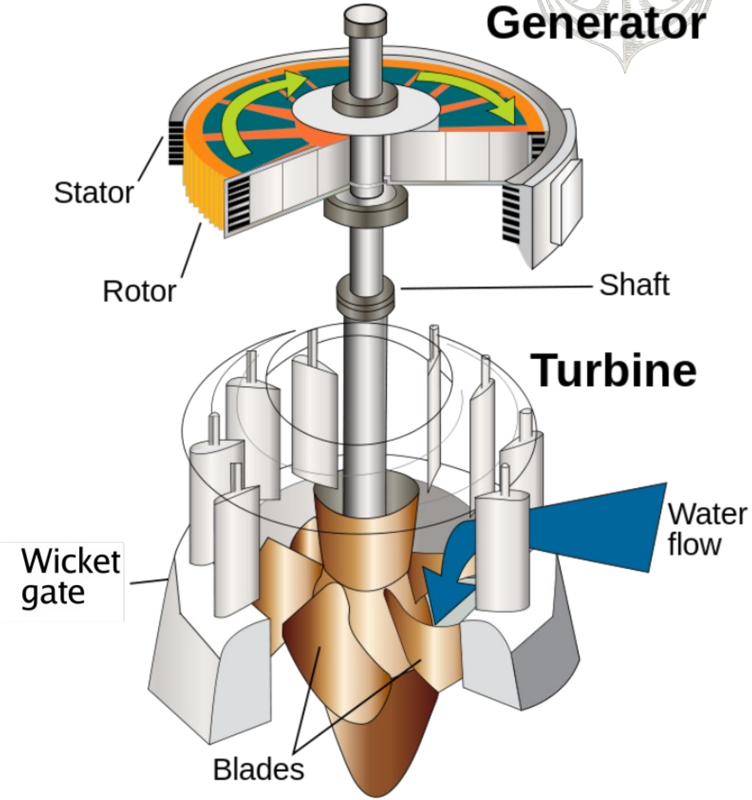
- Growth mostly concentrated in Asia/Pacific



Conventional Dam

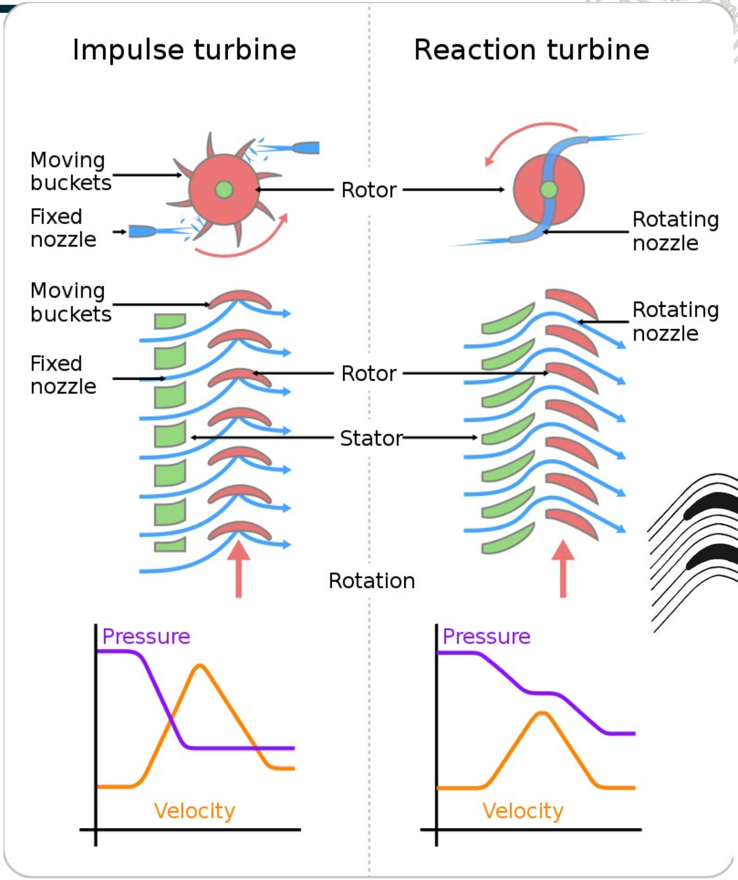


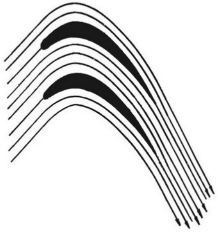
From water wheels to water turbines



Flow in turbines

- 2 main types of turbines
- Impulse turbine:
  - change the direction of the flow; momentum given to blades
  - no pressure change in rotating blades
  - Fixed nozzle reduce pressure & increase velocity (Bernouilli)
  - Well adapted to water
- Reaction turbine:
  - Fluid pressure ⇒ torque on blades
  - Decreasing pressure at blades
  - Pressure casement needed to contain the fluid

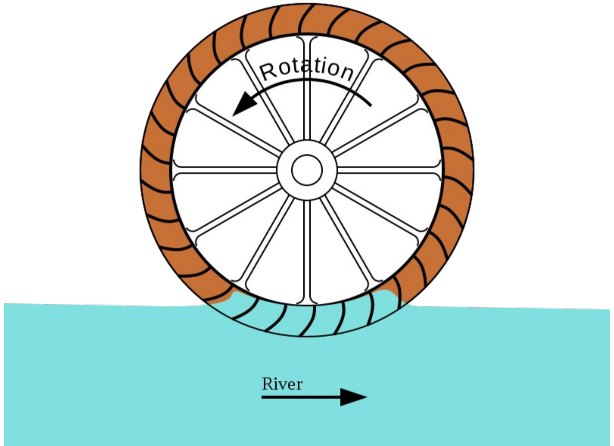




Traditional Water Wheel

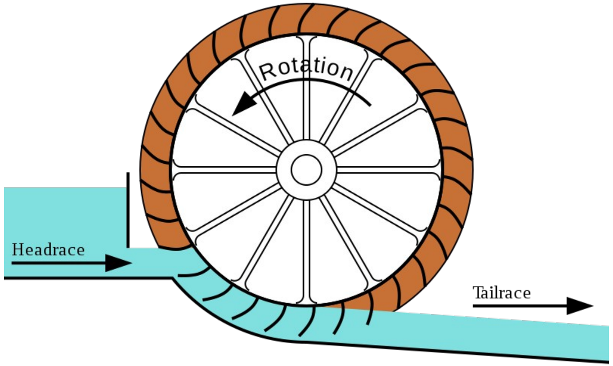
- Traditional water wheels were mostly "reaction" wheel
- Large improvements in mid to late 18th century (John Smeaton)

Stream wheel



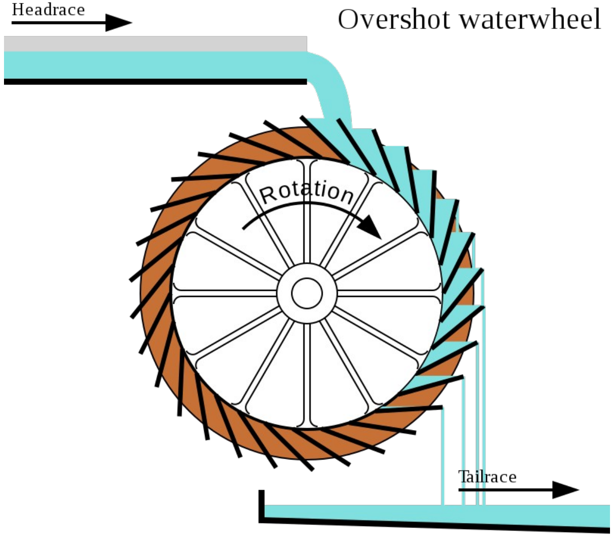
$\eta \approx 20\% \rightarrow 50-60\%$

Undershot waterwheel



$\eta \approx 20\% \rightarrow 50-60\%$

Overshot waterwheel



$\eta \approx 80-90\%$

Efficiency measurement

- Power $P = \eta \times \rho \times g \times h \times \dot{q}$

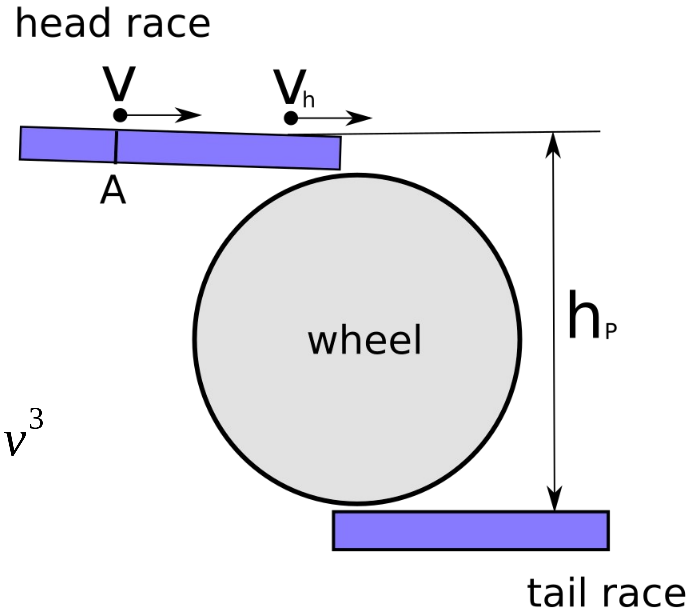
  $\dot{q}$: volume flow rate $(\mathrm{m}^3/\mathrm{s})$

- Velocity head (equivalent height drop)

$$h_v = \frac{v^2}{2g}$$

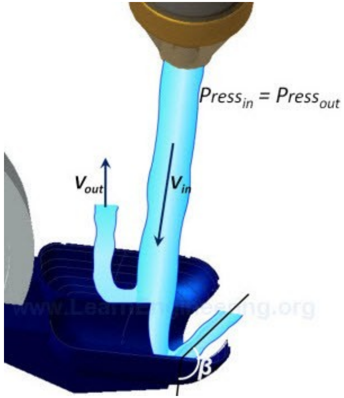
- Overshot: $P \approx \eta \times 10\,000 \times h \times \dot{q}$

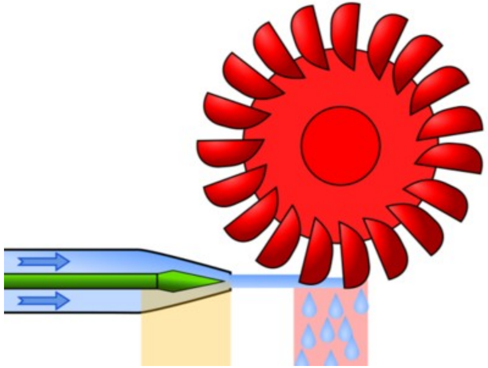
- Undershot: $P \approx \eta \times 500 \times v^2 \times \dot{q} \approx \eta \times 500 \times A \times v^3$



Pelton Wheel

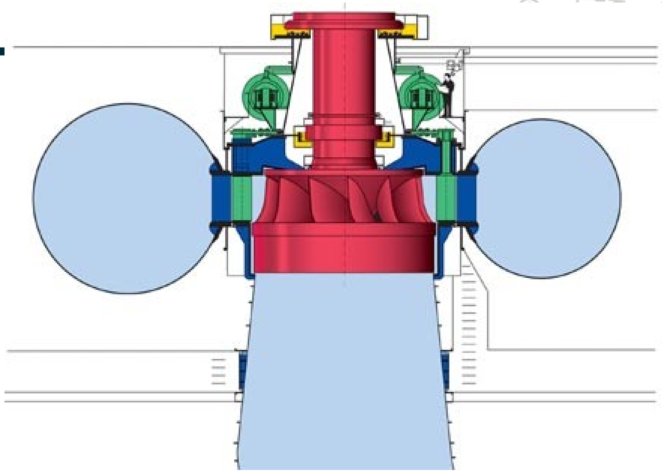
- Impulse water turbine, invented by Lester Allan Pelton in the 1870's
- Nozzles direct forceful, high-speed streams against a series of spoon-shaped buckets
- Water makes a "u-turn" in bucket frame
- Optimal tangential speed = ½ fluid velocity
  ⇒ very little residual velocity ($\eta \cong 95\%$)

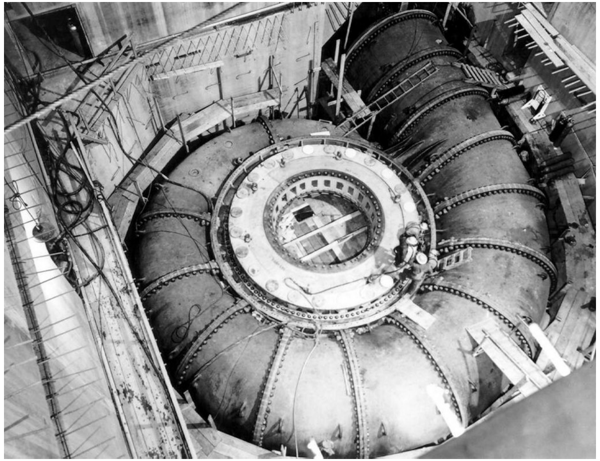




Francis Turbines

- Inward-flow reaction turbine
- Head ~ 40 – 700 m
- Power few kW ⇒ MW
- Yield > 90%
- Components:
  - Spiral casing (or volute casing) with numerous openings to allow the impinge of the working fluid on the blades of the runner
  - Guide & stay vanes: convert pressure into kinetic energy
  - Runner blades: produce the torque
  - Draft tube: connects the runner exit to the tail race (discharge)



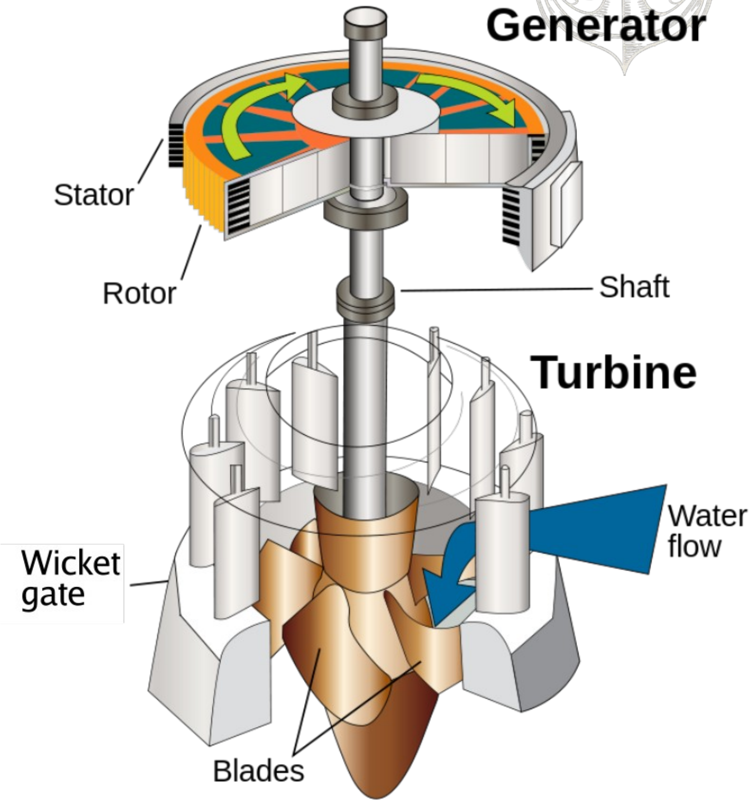


Francis Turbines

- Three Gorges Dam Francis turbine runner, on the Yangtze River, China
- 26 turbines of 710 MW each
- Runner diameter 9,8 m
- Flow 116 000 m^3/s
- Built by Alstom

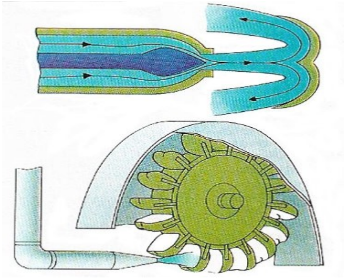
Kaplan Turbines

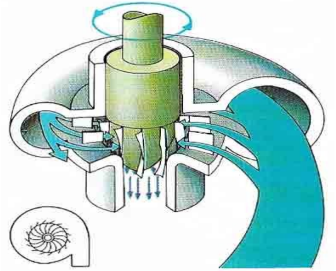
- Inward flow reaction turbine
- Rotating blades with adjustable pitch, evolution of Francis Turbine for low head applications (10 – 70 m)
- Adjustable wicket gate ensure optimal flow angle on the turbine
- 5 – 200 MW Power Range
- Reversible (can be used as a pump)
- Also used in tidal energy applications
- Developed in 1913 by Viktor Kaplan

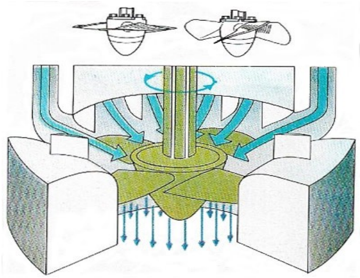


Comparison

- Pelton Turbine: suitable to high head, low flow applications
  e.g.: water piped down a hillside, emerging at lower end from a narrow nozzle a very high velocity
- Francis Turbine: high power, suitable to a large range of application, fall heights 40 – 600 meters
- Kaplan Turbine: suitable to low head, large flow application
  e.g.: dam with large flow rate

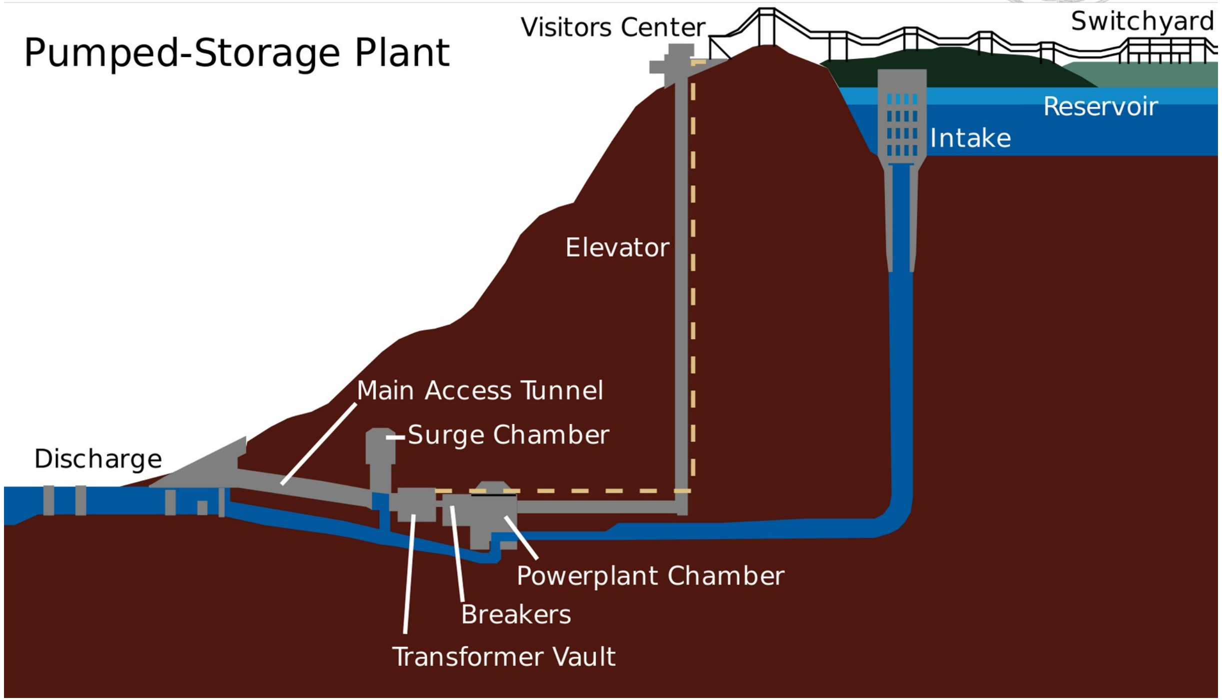






Pumped Storage

- High Capacity energy storage
  - High efficiency
  - High power (GW)
  - Low energy density
  - Important in the context of renewable energies
- See PC 9

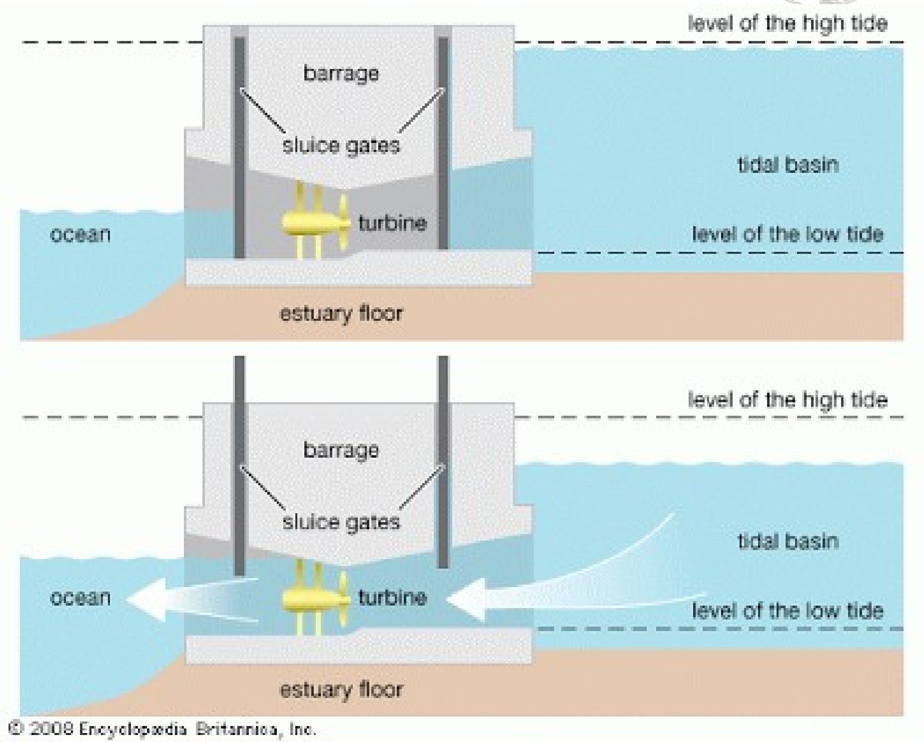


Pumped Storage

Country	Pumped storage generating capacity (GW)	Total installed generating capacity (GW)	Pumped storage/ total generating capacity
China	32.0	1646.0	1.9%
Japan	28.3	322.2	8.8%
United States	22.6	1074.0	2.1%
Spain	8.0	106.7	7.5%
Italy	7.1	117.0	6.1%
India	6.8	308.8	2.2%
Germany	6.5	204.1	3.2%
Switzerland	6.4	19.6	32.6%
France	5.8	129.3	4.5%
Austria	4.7	25.2	18.7%

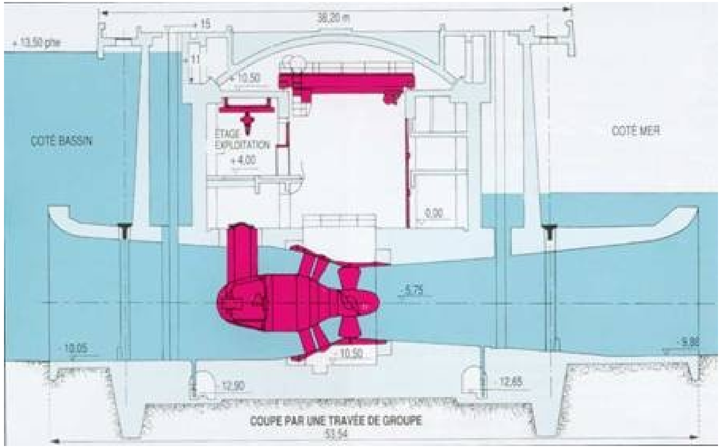
Tide Energy

- Exploit the height difference between low & high tides
  (up to ~ 10 m)
- Predictable & regular
- But intermittent & low yield (low head)



La Rance

- Oldest tidal power station in the world (1966)
- 24 bulge turbines, peak output 240 MW
  - Axial turbine directly coupled to an alternator
  - Adapted to very low head (2 – 15 m) and large flows, reversible
- Electricity cost ~ 0.12€/kWh



Lecture 7 – Wind & Hydro Energies

I. Hydraulic energy

II. Wind Resources

III. Betz Limit

IV. Basics of aerodynamics

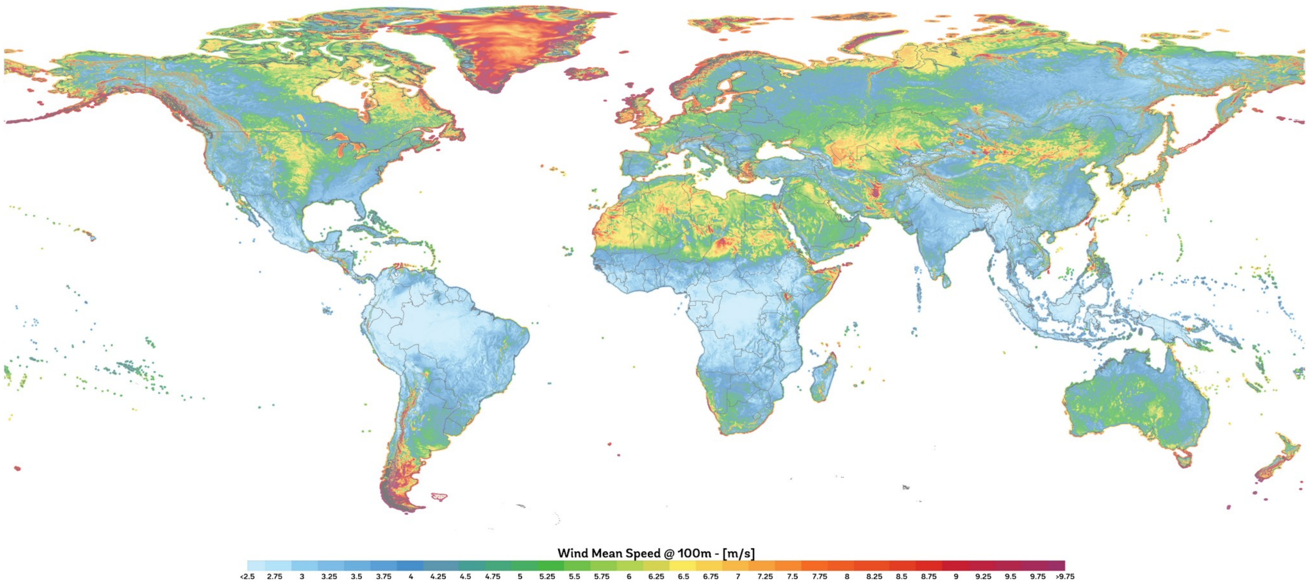
V. Wind Turbines

VI. Submarine turbines

VII. Conclusions & Outlook

Gross Figures

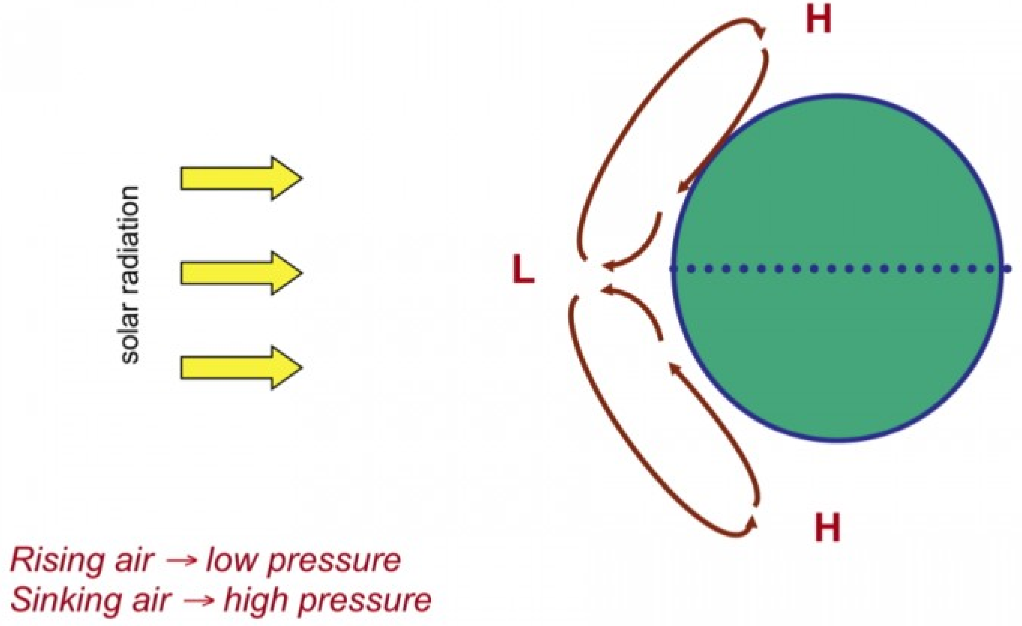
- Winds are present everywhere
- Global kinetic Energy



Global Wind Atlas, Technical University of Denmark (DTU).

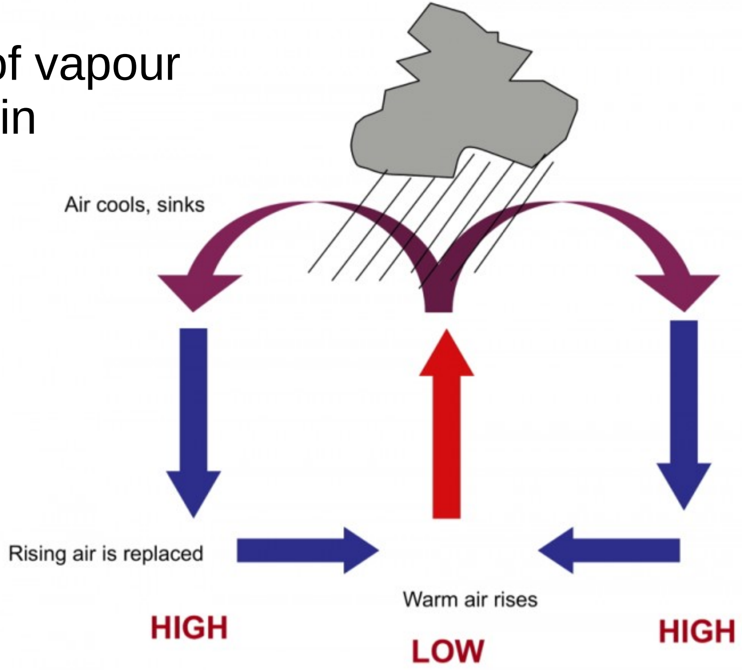
Origin of winds – Hadley cells

- Warm air at equator creates under-pressure and rises
- Rising air creates a circulation cell



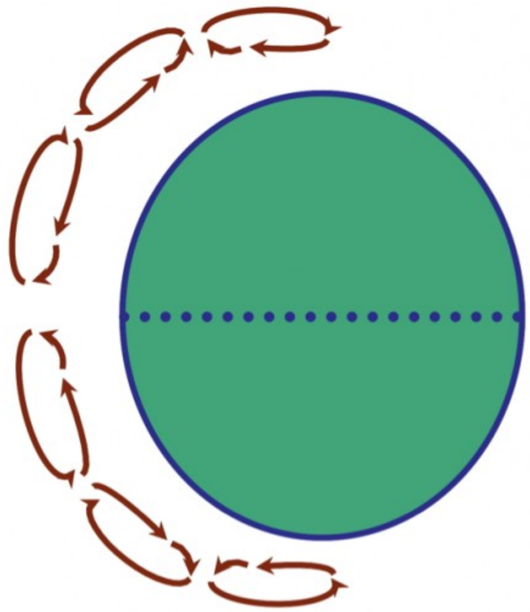
Pressure gradients

- Hot, moisture-laden air rises
- Increased altitude ⇒ colder ⇒ decrease of vapour saturation pressure ⇒ condensation ⇒ rain
- Air then cools (radiation) and sinks
- Generates Hadley circulations cells



Earth rotation

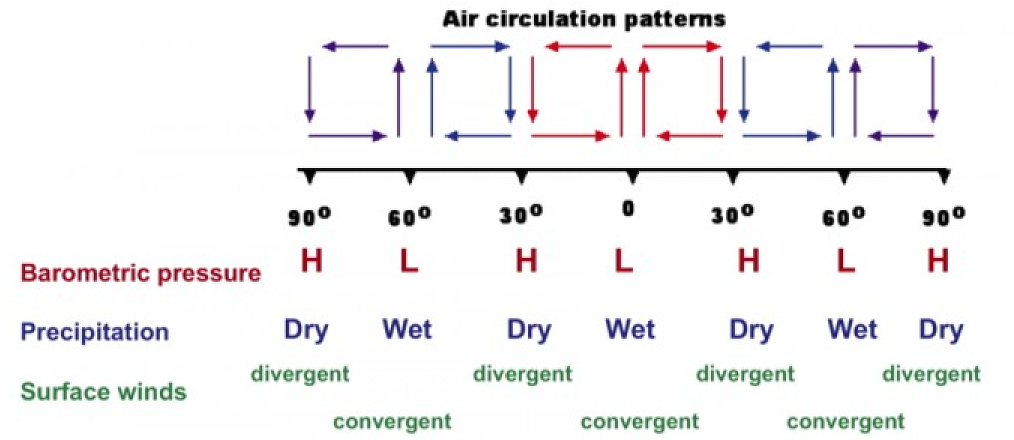
- In the absence of Earth rotation one would have two large Hadley cells
- Coriolis rotation causes winds to be deflected
- Results in the large Hadley cell to be broken in ~3 components

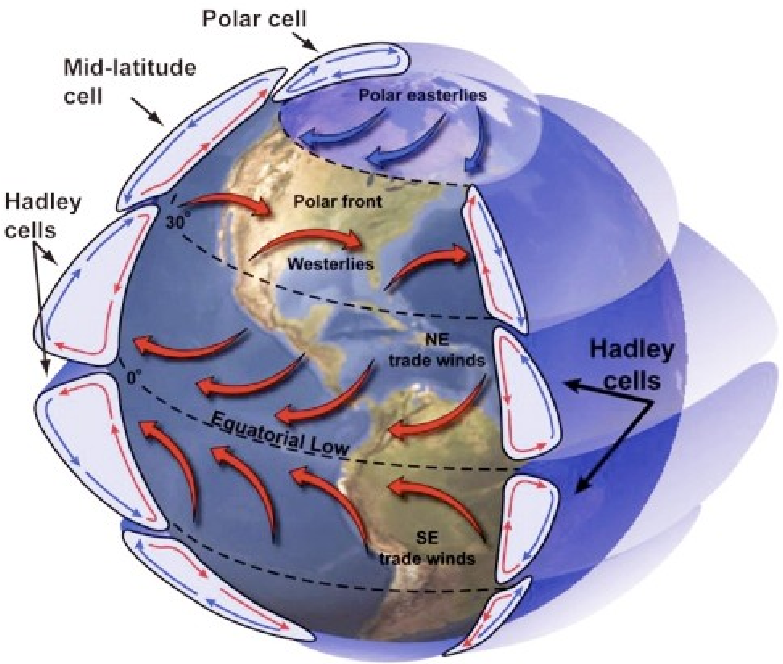


https://www.e-education.psu.edu

Overall pattern

- ~ 6 cells in latitude
  - Hadley & Polar cells act as heat engines (heat ⇒ kinetic energy)
  - Mid-latitude cells act as heat pumps (kinetic energy ⇒ heat)





Total energy in winds

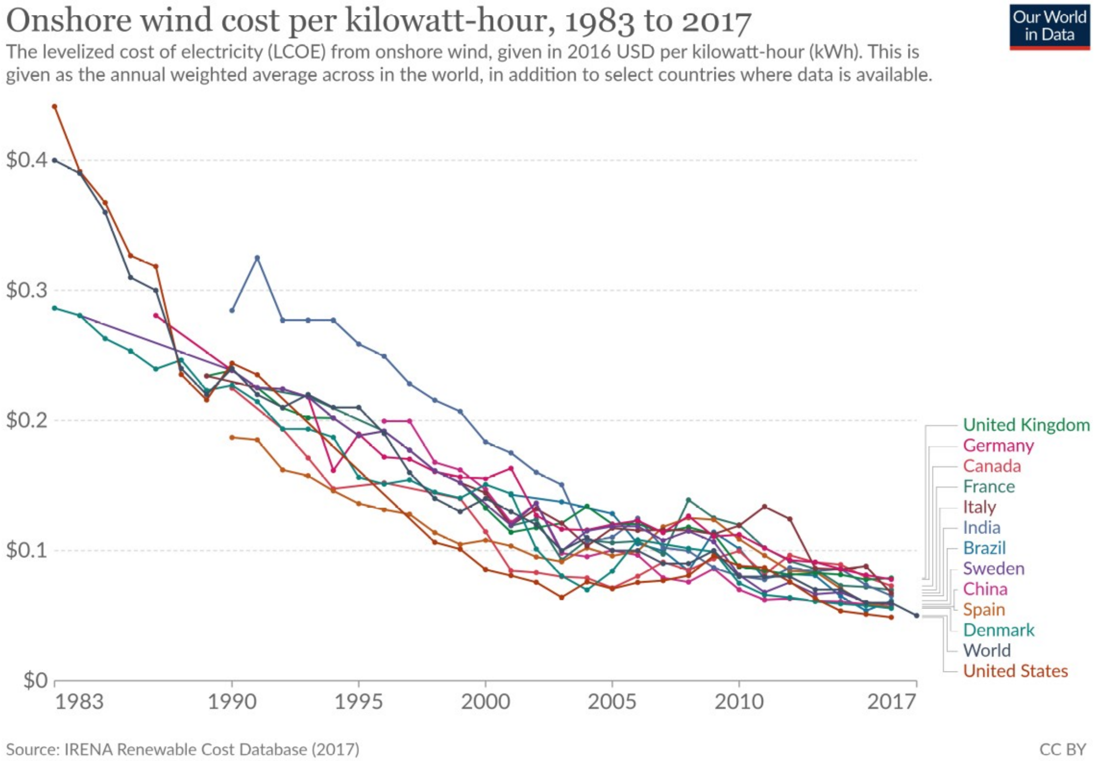
- Airflow kinetic energy $E=\int_S \rho \frac{v^2}{2} \mathrm{d}S$
- Estimated global wind kinetic energy: $\langle E \rangle=\int_S \rho \frac{v^2}{2} \mathrm{d}S \approx 1.\,\mathrm{MJ/m^2}$
- Estimated wind potential depends on local conditions, technological aspects, etc.
- The total amount of economically extractable power available from the wind is considerably more than present human power use from all sources
- Power through a surface:

$$P=\frac{1}{2}\rho v^3 S$$

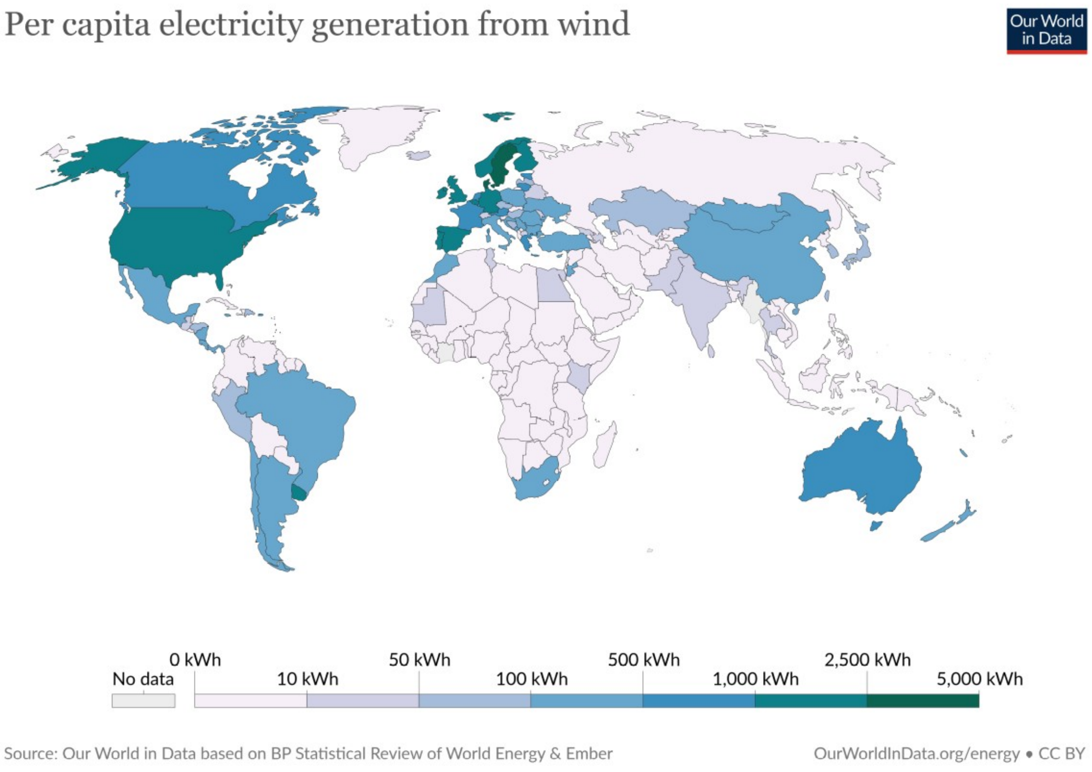
See PC

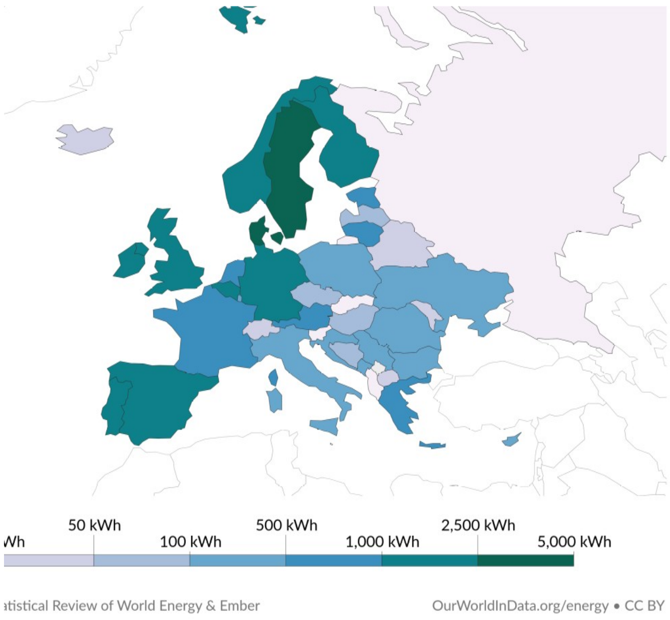
Onshore Wind Cost

- Continuous cost reduction
- Wind energy now competitive with fossil



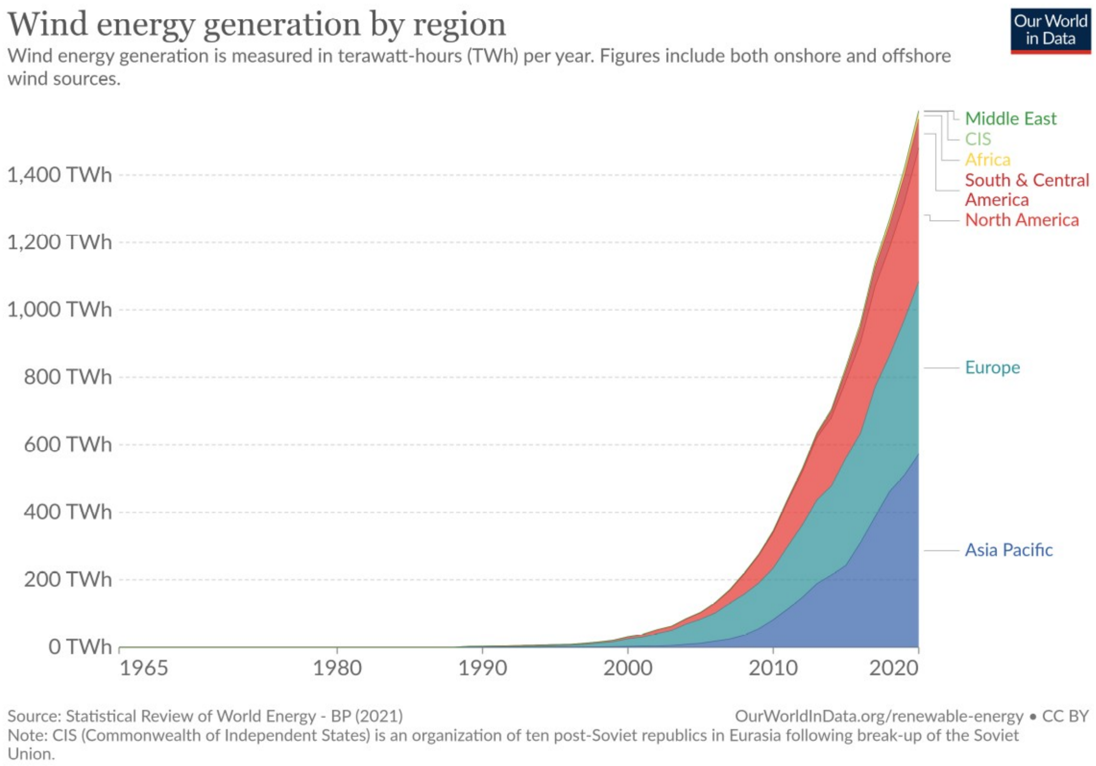
Wind energy per capita





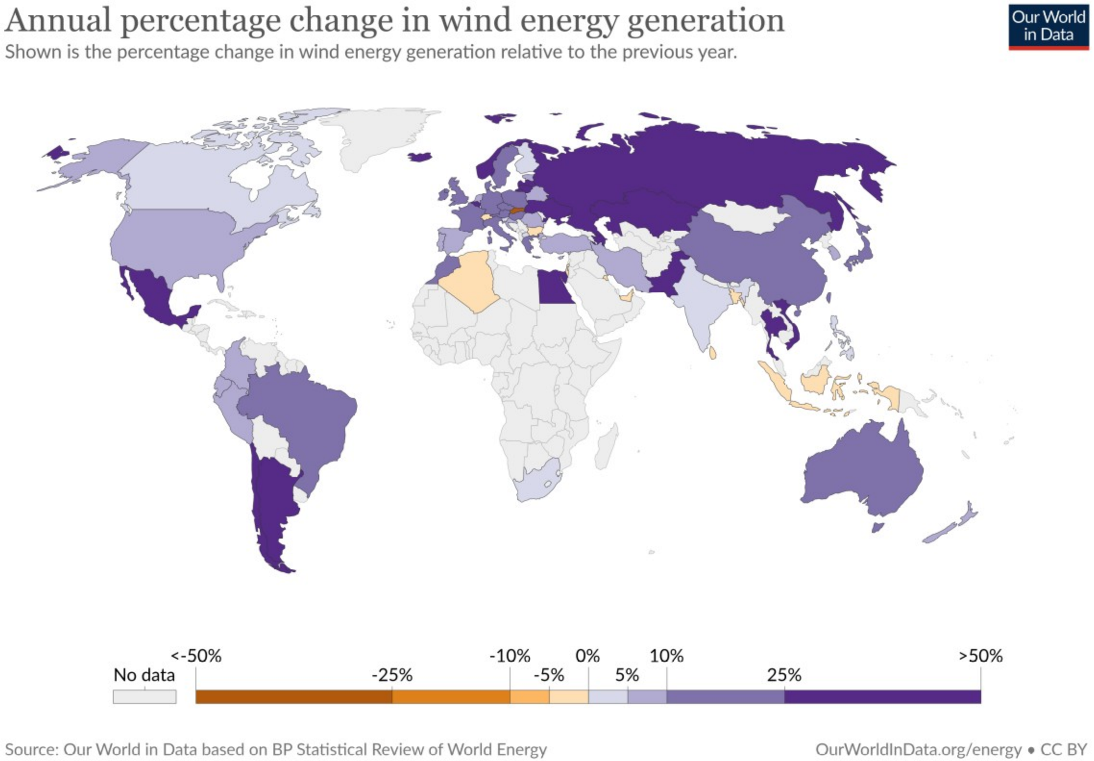
Take-off

- Recent development driven by lower prices



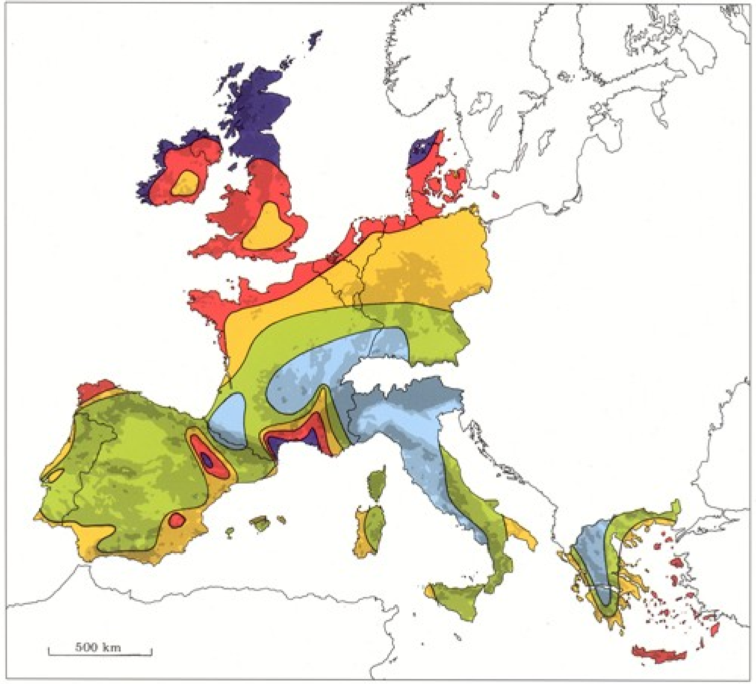
Growth

- Africa mostly left behind



European Wind Atlas

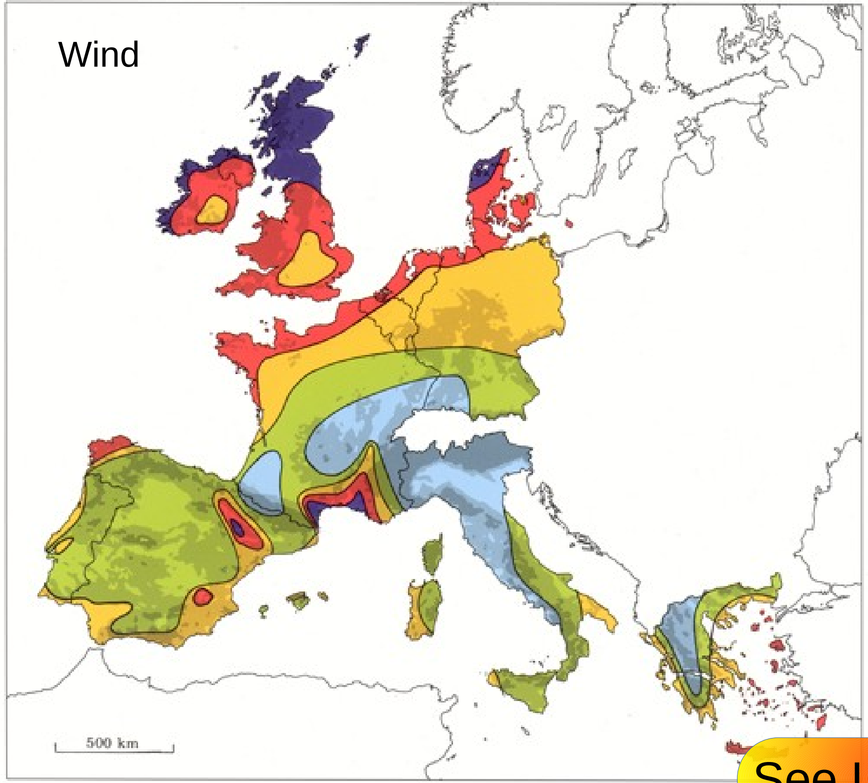
- Very strong and regular winds in northern Europe
- Strong potential in North-Sea, UK, and northern coast of France, Belgium, Netherlands, Germany
- See https://map.neweuropeanwindatlas.eu/

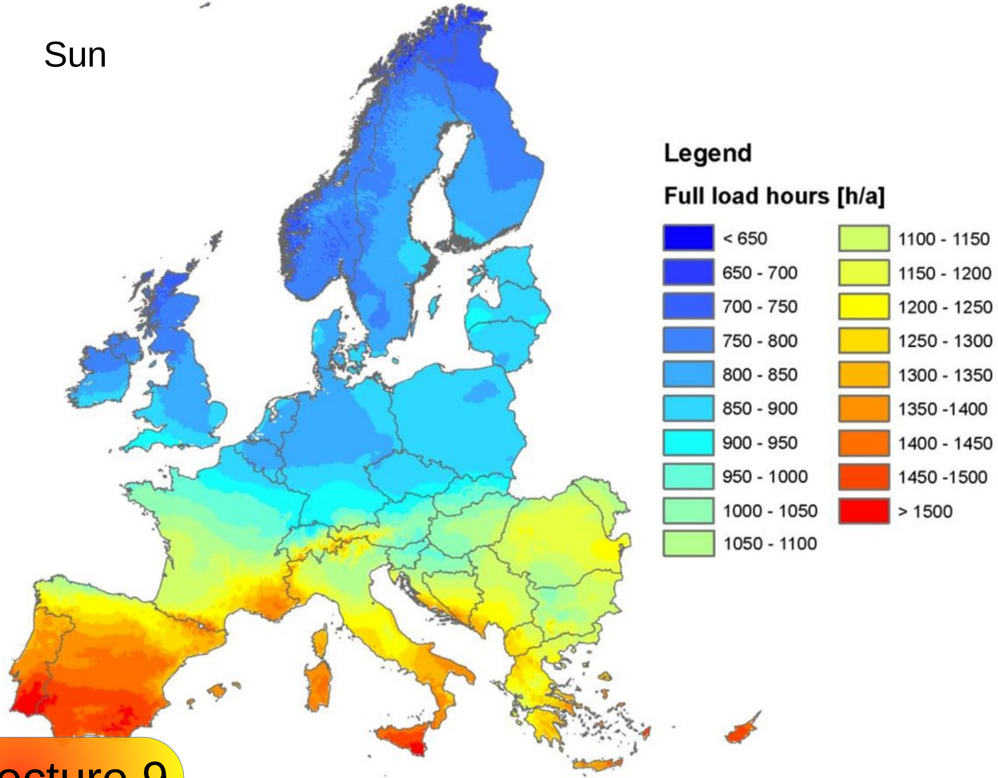


Wind resources[1] at 50 metres above ground level for five different topographic conditions

	Sheltered terrain[2]		Open plain[3]		At a sea coast[4]		Open sea[5]		Hills and ridges[6]	
	$m\,s^{-1}$	Wm^{-2}	$m\,s^{-1}$	Wm^{-2}	$m\,s^{-1}$	Wm^{-2}	$m\,s^{-1}$	Wm^{-2}	$m\,s^{-1}$	Wm^{-2}
	> 6.0	> 250	> 7.5	> 500	> 8.5	> 700	> 9.0	> 800	> 11.5	> 1800
	5.0-6.0	150-250	6.5-7.5	300-500	7.0-8.5	400-700	8.0-9.0	600-800	10.0-11.5	1200-1800
	4.5-5.0	100-150	5.5-6.5	200-300	6.0-7.0	250-400	7.0-8.0	400-600	8.5-10.0	700-1200
	3.5-4.5	50-100	4.5-5.5	100-200	5.0-6.0	150-250	5.5-7.0	200-400	7.0- 8.5	400- 700
	< 3.5	< 50	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 7.0	< 400

European Wind/Sun Atlas





See Lecture 9

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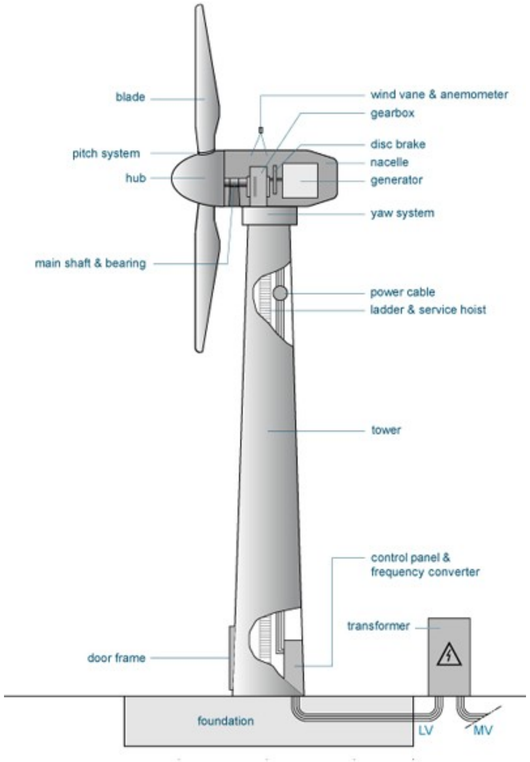
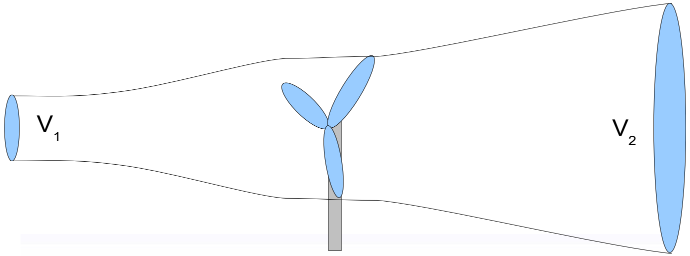
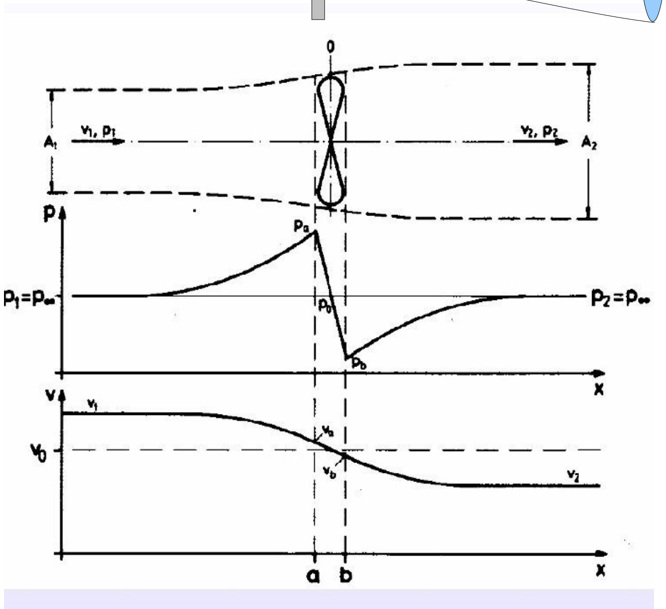
Yield of a wind turbine





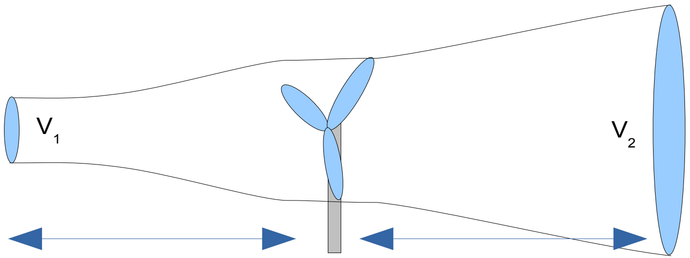


Betz's Limit – Math

- Idealized flow (perfect fluid, no vorticity ⇒ Bernoulli)

$$\frac{p_1}{\rho}+\frac{v_1^2}{2}=\frac{p'_1}{\rho}+\frac{v'^2_1}{2} \quad \text{and} \quad \frac{p_2}{\rho}+\frac{v_2^2}{2}=\frac{p'_2}{\rho}+\frac{v'^2_2}{2}$$

- Continuity: $v'_1=v'_2\equiv v_{avg}$



$p_1=p_0$ p'_1 p'_2 $p_2=p_0$

$$\Rightarrow \quad p'_1-p'_2=\ldots=\rho\left(\frac{v_1^2}{2}-\frac{v_2^2}{2}\right)$$

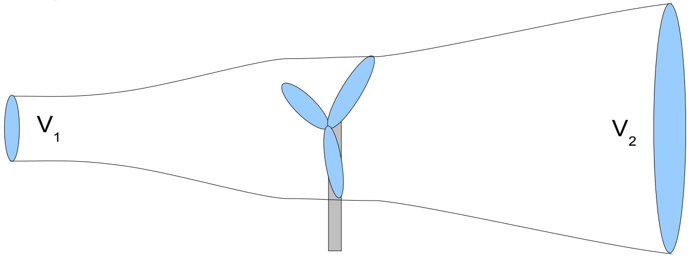
Betz's Limit – Math

- Thrust on rotor from momentum: $F = -\frac{\mathrm{d}\,p_{\mathrm{air}}}{\mathrm{d}\,t} = \dot{m}(\vec{v}_1 - \vec{v}_2) = \rho\, v_1 S_1 (v_1 - v_2)$
- Can be expressed as function of pressure difference: $F = (p'_1 - p'_2) \times S$
- Equating two expressions gives velocity at rotor: $v_{\mathrm{avg}} = \frac{v_1 + v_2}{2}$
- Deceleration factor: (“*axial induction factor*”) $v_2 = a \times v_1, \quad a \in [0,1]$
- Turbine power: $P = F \times v_{\mathrm{avg}} = \rho\, S\, v_1^3 \frac{(1+a)(1-a^2)}{4}$

Betz's Limit – Math

- Thrust on rotor $\vec{F} = -\frac{\mathrm{d}\,\vec{p}_{\mathrm{air}}}{\mathrm{d}\,t} = \dot{m}(\vec{v}_1 - \vec{v}_2) = \rho\, v_1 S_1 (v_1 - v_2)$
- Idealized flow (perfect fluid, no vorticity ⇒ Bernoulli)

$$\frac{p_1}{\rho} + \frac{v_1^2}{2} = \frac{p'_1}{\rho} + \frac{v'^2_1}{2} \quad \text{and} \quad \frac{p_2}{\rho} + \frac{v_2^2}{2} = \frac{p'_2}{\rho} + \frac{v'^2_2}{2}$$



$$p'_1 - p'_2 = \left(p_0 + \rho \frac{v_1^2}{2} - \rho \frac{v_{\mathrm{avg}}^2}{2} \right) - \left(p_0 + \rho \frac{v_2^2}{2} - \rho \frac{v_{\mathrm{avg}}^2}{2} \right) = \rho \left(\frac{v_1^2}{2} - \frac{v_2^2}{2} \right)$$

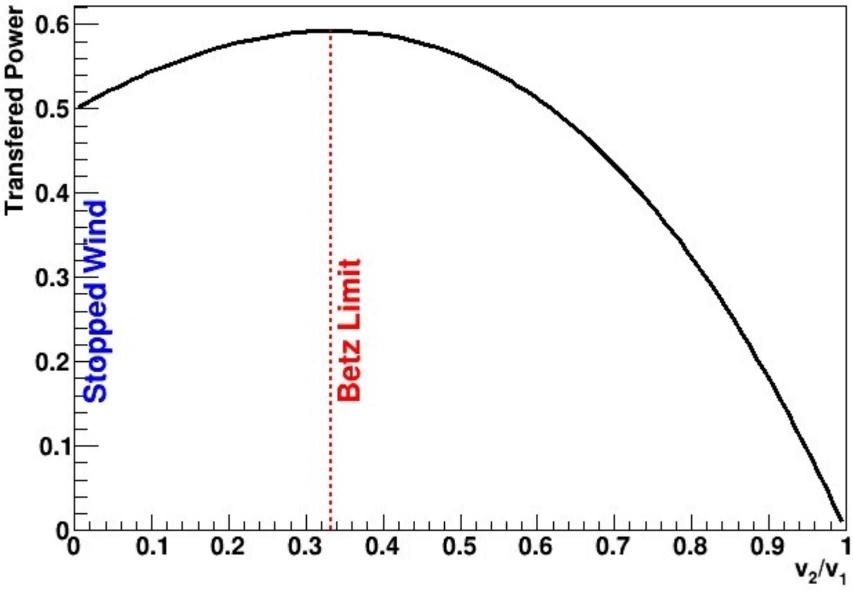
Betz's Limit

- Turbine yield

$$C_p = \frac{P_{\text{turbine}}}{P_{\text{wind}}} = \frac{(1+a)(1-a^2)}{2}$$

- Maximal power obtained for a = 1/3.
- In that case, 16/27≃ 59% of the wind power is extracted

See PC



Beating Betz's limit

- Beating Betz's limit is very challenging
- Some concepts discussed in the literature:
  - Two or more disks in series (Loth, J.L. & McCoy, H., 1983) ⇒ $C_p \simeq 64\%$
  - Vertical Axis turbines (Darrieus type) with several rotors
  - …
- The efficiency gain is not worth the much larger complexity

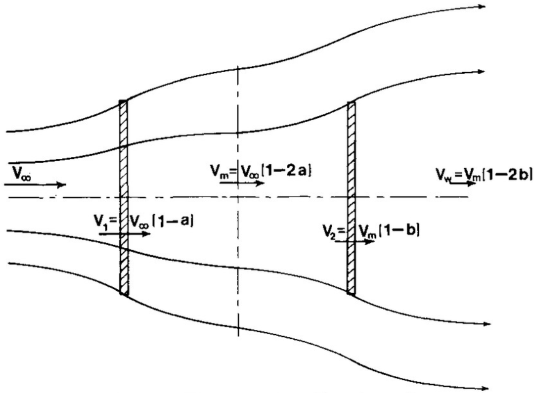


Fig. 1 Two actuator disks in series.

Betz vs Hydro

- Wind turbines are limited to $C_p \simeq 59\%$
- Water turbine (dam) go up to $C_p \simeq 95\%$

Why?

- Difference in fluid flow: immersed in fluid or not (interaction of neighbouring fluid resisting to pressure)

Effect of rotation

- “Tip Speed Ratio” (TSR): Speed ratio at end of blades:
  U: speed of the wind (far away)
  Ω: angular rotation speed
  R: blade length

$$\lambda = \frac{\Omega R}{U}$$

- Rotation transforms Thrust into Torque.
- Betz's limit only considers thrust and ignores rotation
- But wind behind the turbine must have some kinetic momentum!

Glauert's limit

- Introduction of an "*angular induction factor*"
  ω is the fluid angular rotation speed

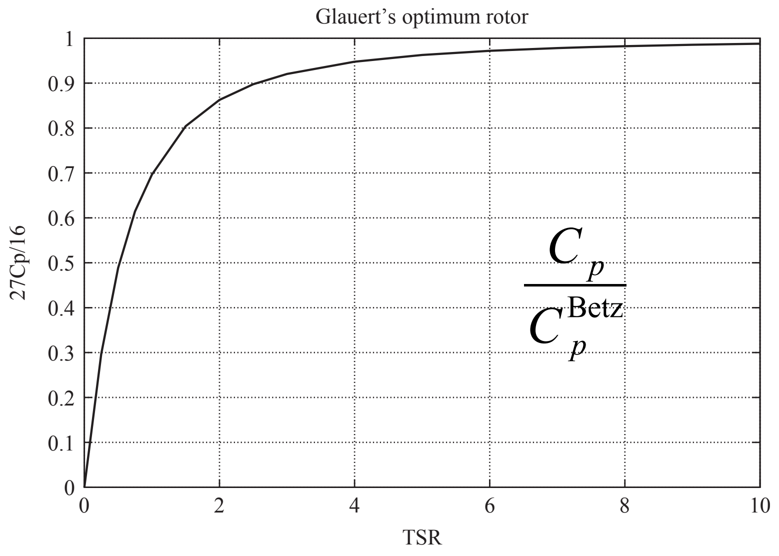
$$a' = \frac{\omega}{2\Omega}$$

- Elementary torque for a slide dr is:

$$dM = 4 r^3 v_1 (1-a) a' dr$$

- 2 parameters now need to be optimized.
  Net result (Glauert, 1993)

$$a' = \frac{1-3a}{1+4a}$$

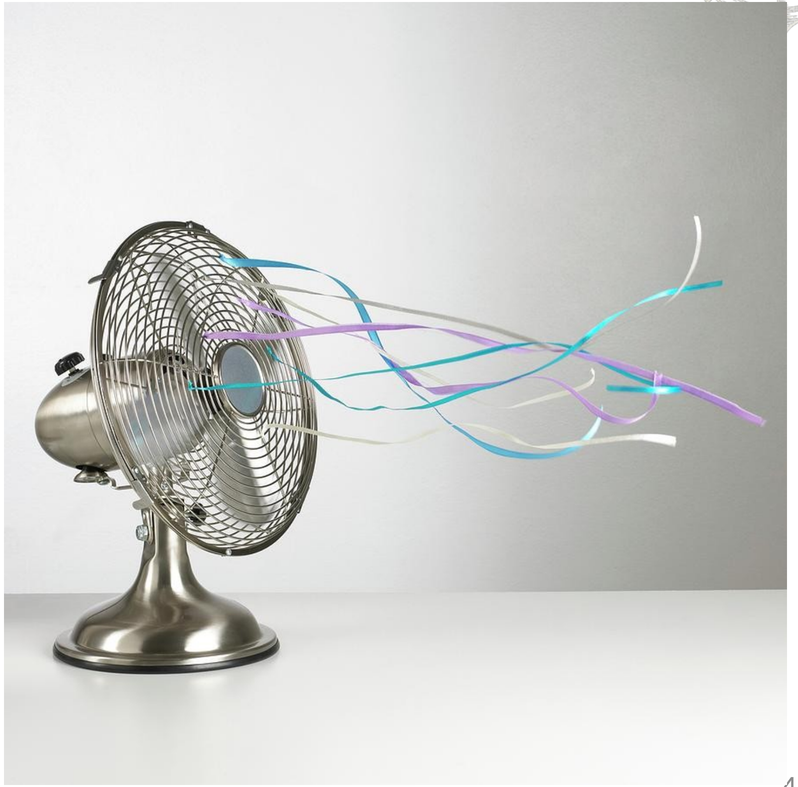


- "*Swirl*" losses at low tip-speed ratio
- Blades are more efficient at large velocities
  Apparent (rotating) winds becomes dominant

See PC

Glauert's limit for dummies

- At low velocity, a fan produced a turbulent air flow
- Need high velocity & low incidence blades to produce a ~ parallel flow



Lecture 7 – Wind & Hydro Energies

I. Hydraulic energy

II. Wind Resources

III. Betz Limit

IV. Basics of aerodynamics

V. Wind Turbines

VI. Submarine turbines

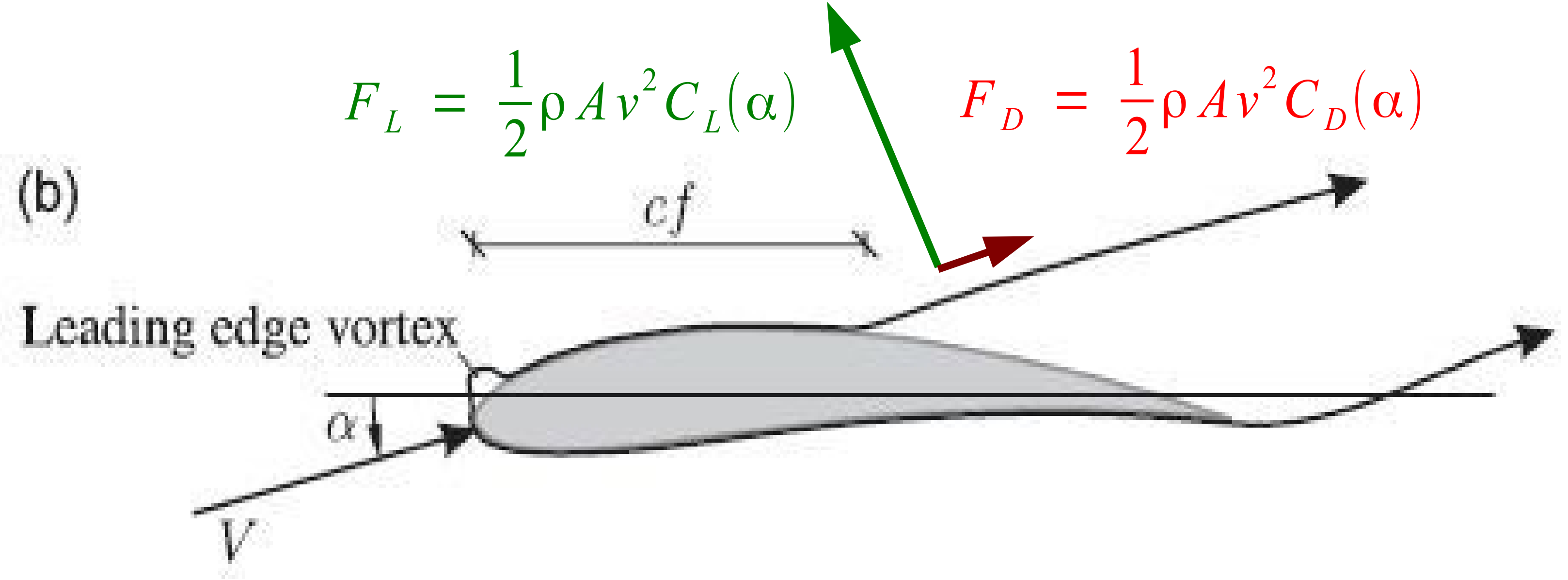
VII. Conclusions & Outlook

Lift & Drag Forces

- Drag force parallel to air flow (resist to movement)
- Lift for orthogonal to it (makes birds & planes fly)
- Depends on square of wind speed

$$F_L = \frac{1}{2}\rho A v^2 C_L(\alpha)$$

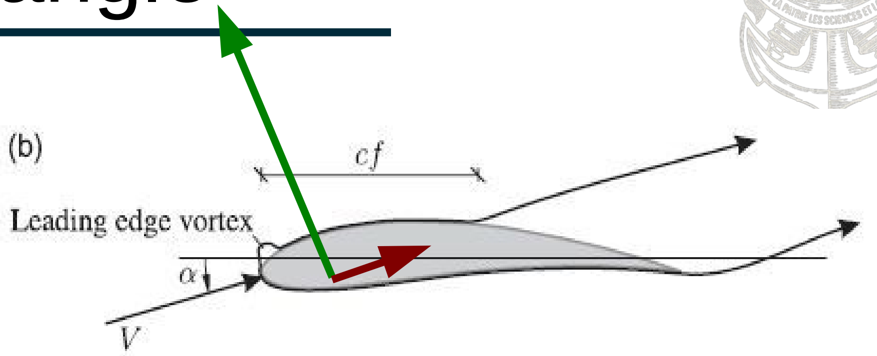
$$F_D = \frac{1}{2}\rho A v^2 C_D(\alpha)$$



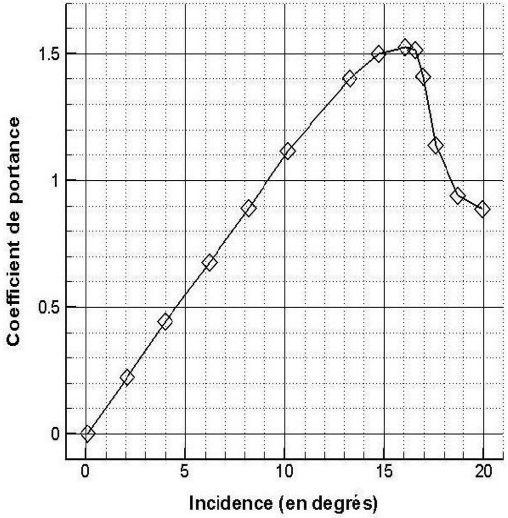
Variation with attack angle

$$F_L = \frac{1}{2}\rho A v^2 C_L(\alpha)$$

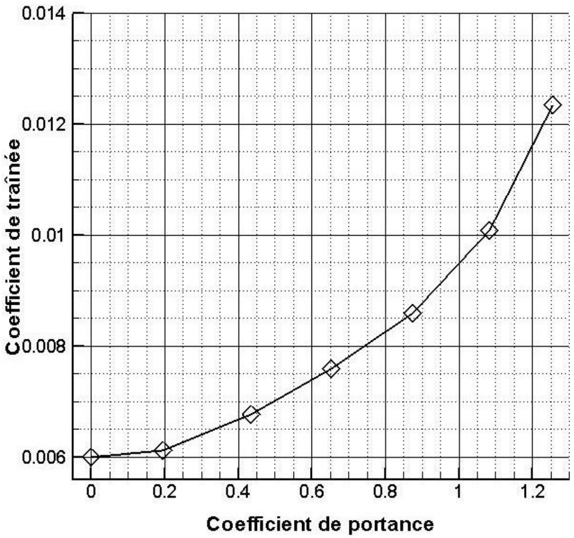
$$F_D = \frac{1}{2}\rho A v^2 C_D(\alpha)$$



C_L



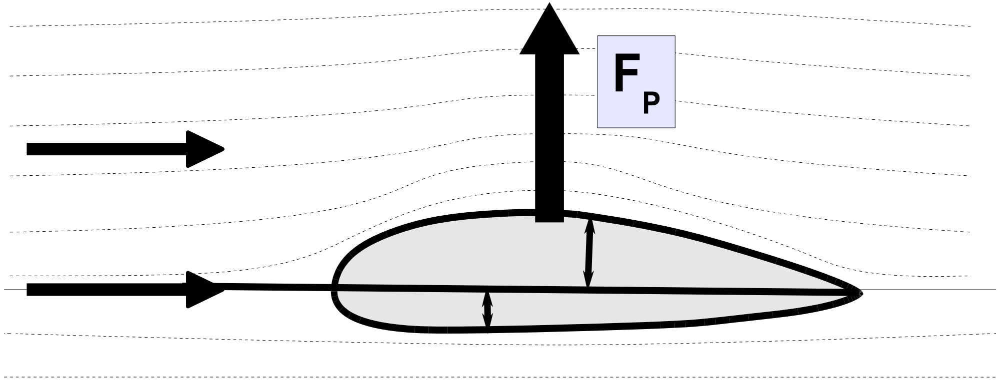
C_D

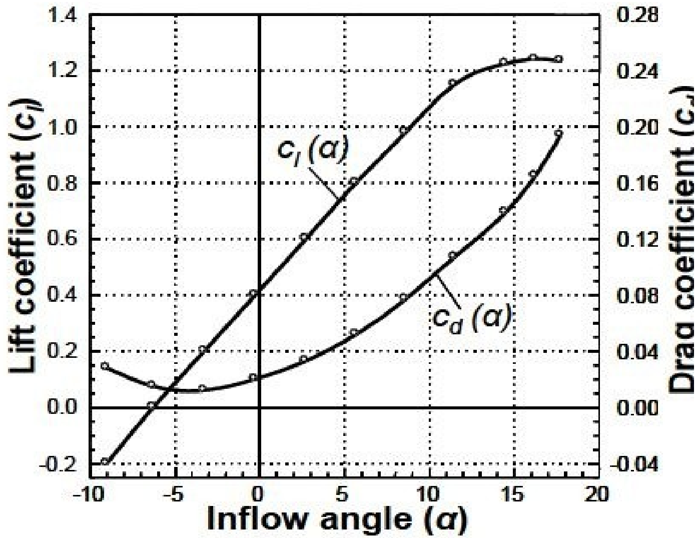


C_L

Lift force at zero angle

- Lift force can be non-zero at zero attack angle
- Depends on wing profile





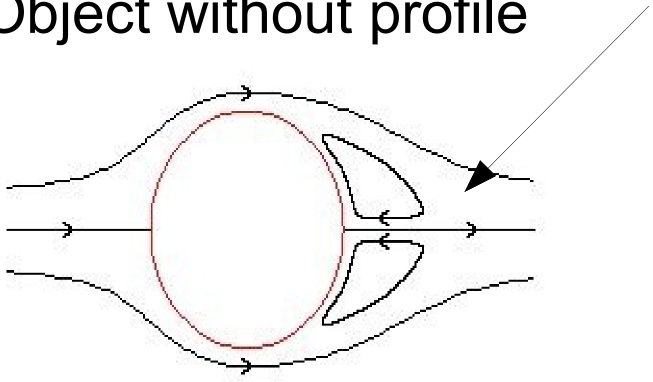
Origin of Drag Force

- Only appearing in viscous fluids

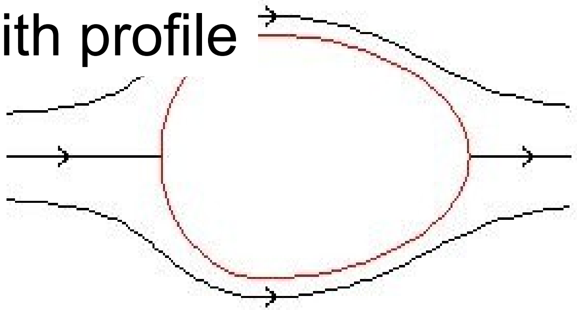
Object without profile

Two symmetrical vortices

Under pressure → drag force

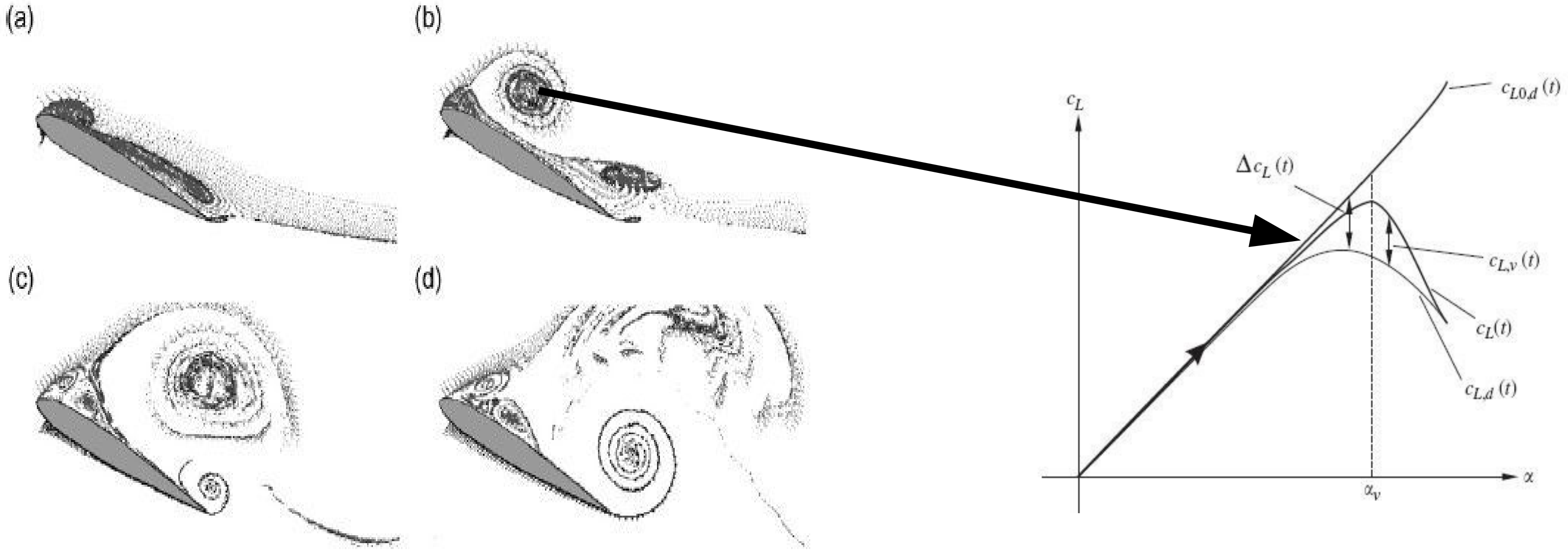


Object with profile



Stall Speed

- At large speed/attack angle, lift force is significantly reduced by turbulence
- Sudden drop at “stall angle”

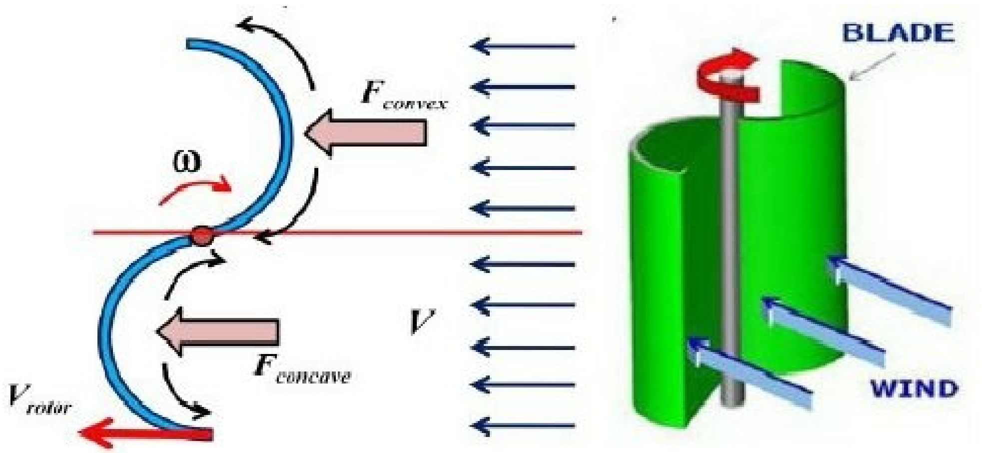


Lecture 7 – Wind & Hydro Energies

Drag Force Wind Mill

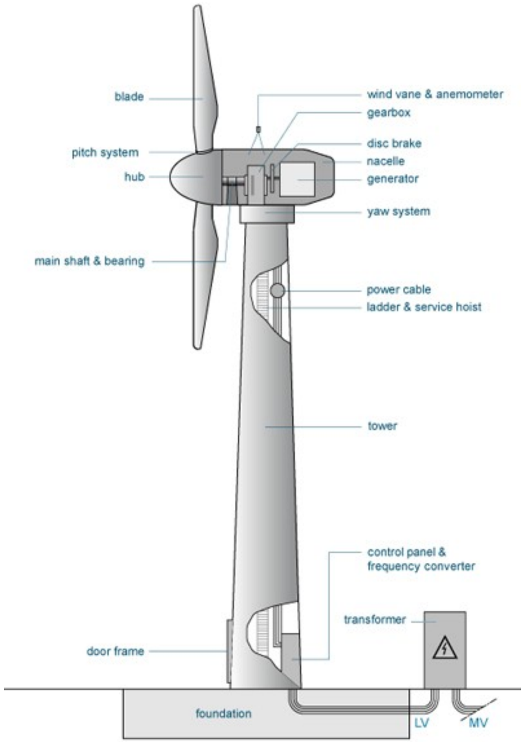
- Drag force larger on concave side than on convex side
- Induces torque

DOI: 10.1016/j.egypro.2015.03.259



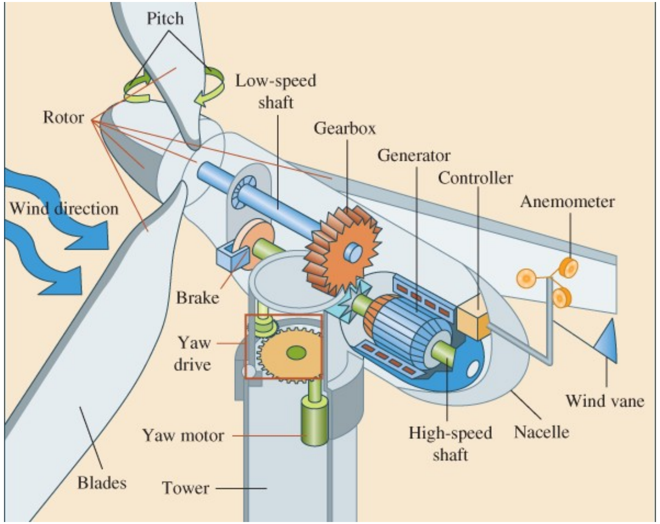
Traditional Mill (low velocity)

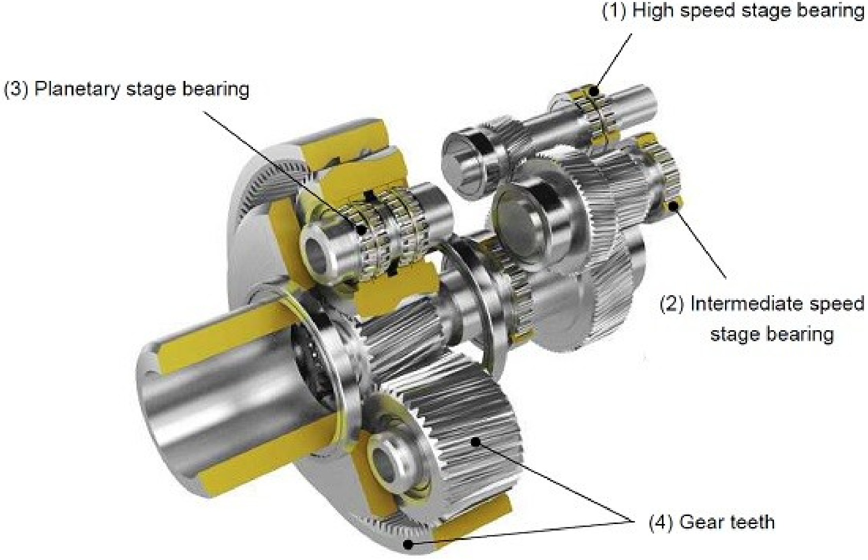
Horizontal Axis Wind Turbine



Components – Gearbox

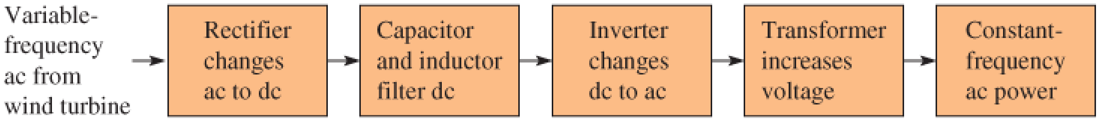
- Output frequency must be adjusted precisely to network (50 or 60 Hz)
- Most turbines use a gearbox connected to high-speed shaft
- Undergo severe and variable transient loading (start-up, shut-down, grid connection, wind fluctuations)





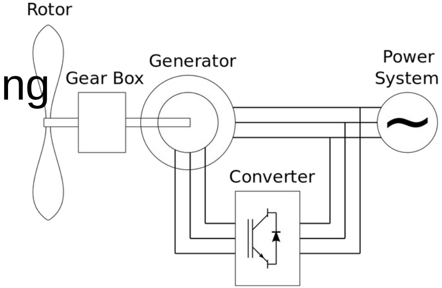
Frequency control

- Adjustment of rotational speed of rotor via
  - Pitch : rotational angle of the blades
  - Yaw: direction the wind turbine blades & nacelle are facing
- Allow the turbine to run freely at any speed
  - Need a power electronic frequency converter (full effect converter)



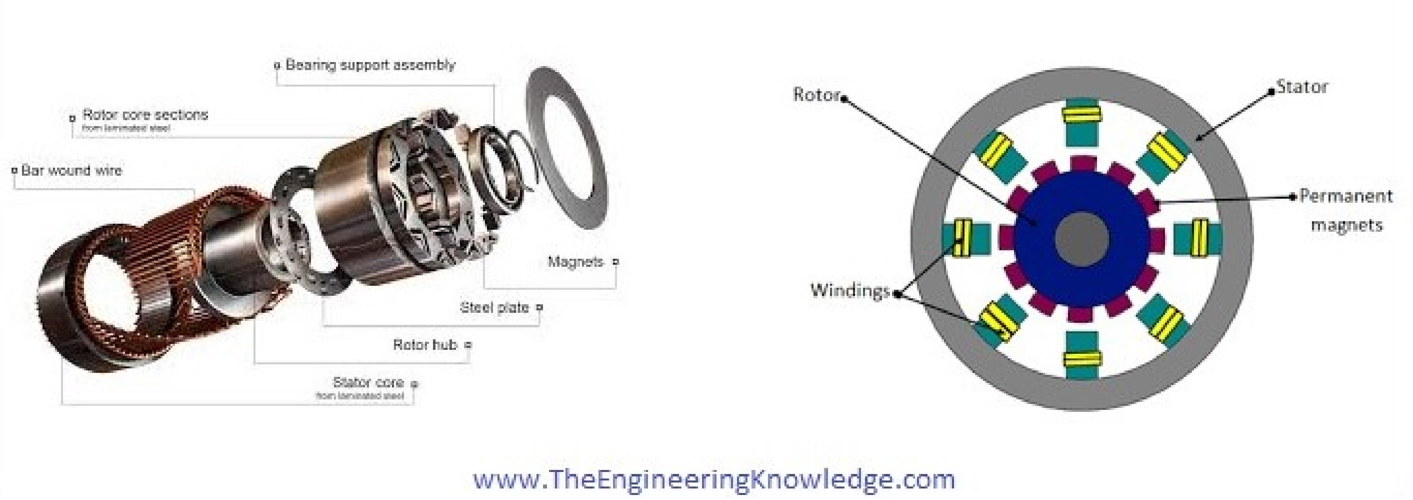
See Lecture 9

- Use a double-feed, inductive-type generator (DFIG)
  - Use two three-phase windings, one stationary and one rotating
  - One winding directly connected to the grid
  - Can accept varying input speed (in some range)
  - See lecture notes



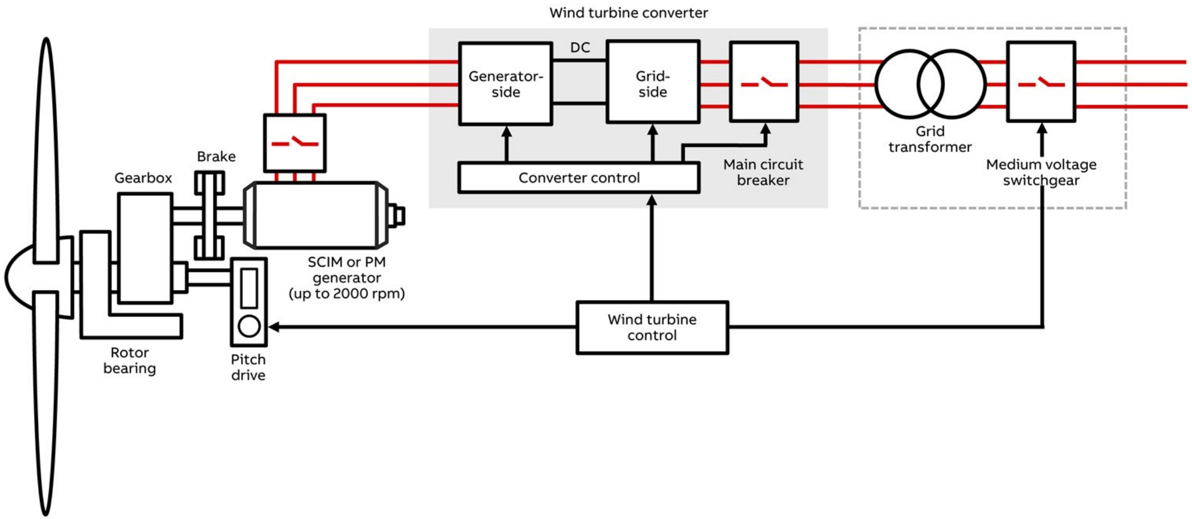
Direct drive turbines

- Use permanent magnet synchronous generator (instead of coil)
- Allow slower rotational speed input, less constraints, reduced noise, longer lifetime, reduced maintenance
- More costly & require rare earth elements (Neodymium)
- ~5% of current turbines, increasing (in particular for off-shore)

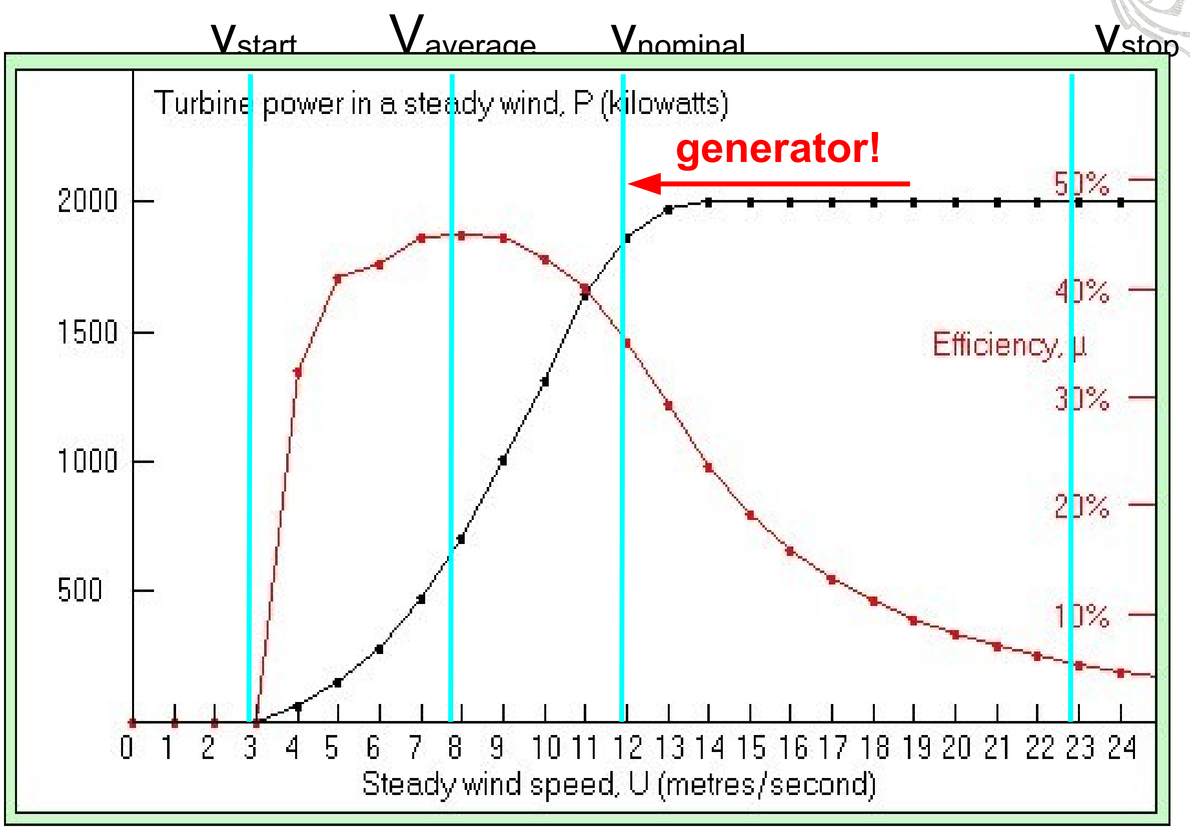


Direct drive turbines

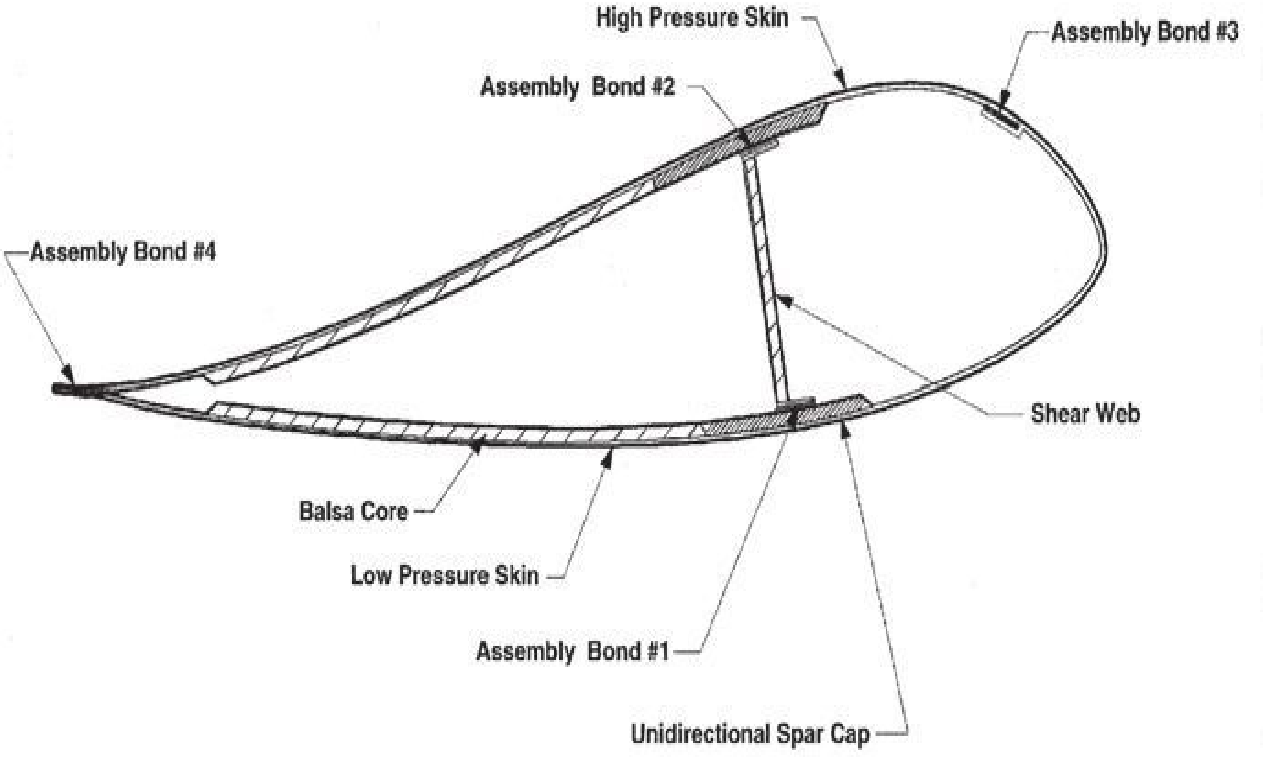
- Need DC ⇒ AC conversion system



Typical Power Curve of a wind turbine



Structure of blades



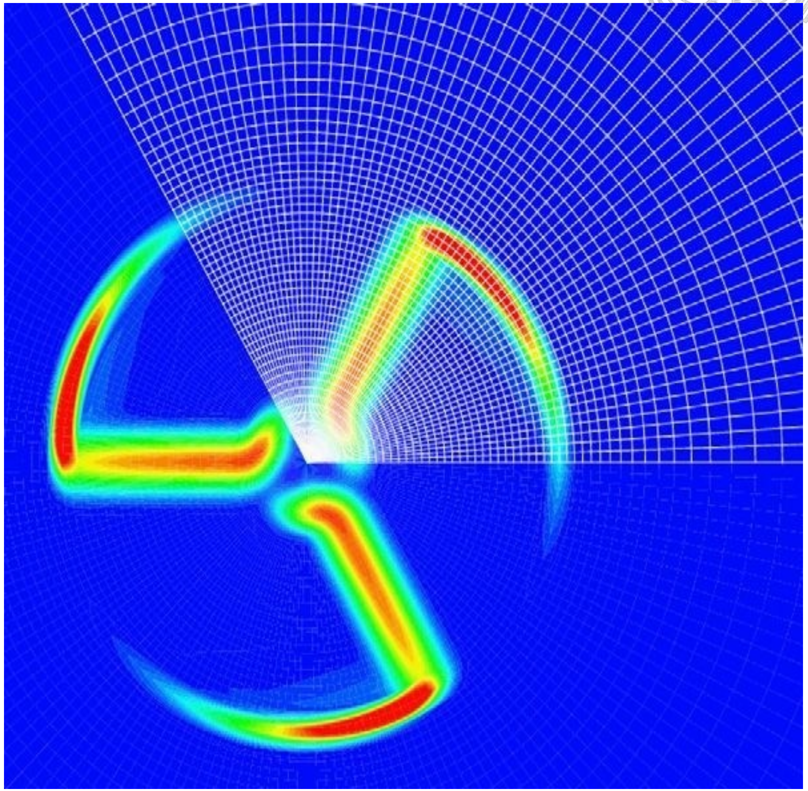
Blades

- Mostly made of fiber-reinforced polymers (FRPs)
- Some are reinforced with Carbon Nano-tubes

Transportation

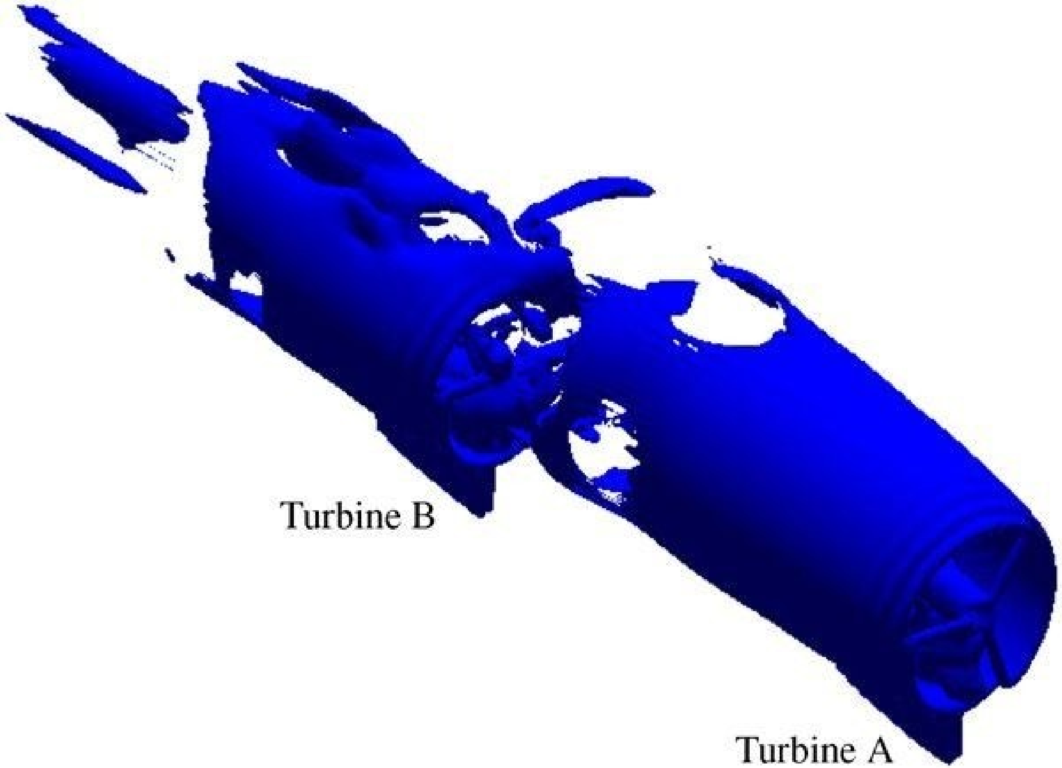
Vorticity & interaction between blades

- Actuator line computation showing vorticity contours and part of computational mesh around a three-bladed rotor.(Mikkelsen R., 2003)



Interactions between turbines

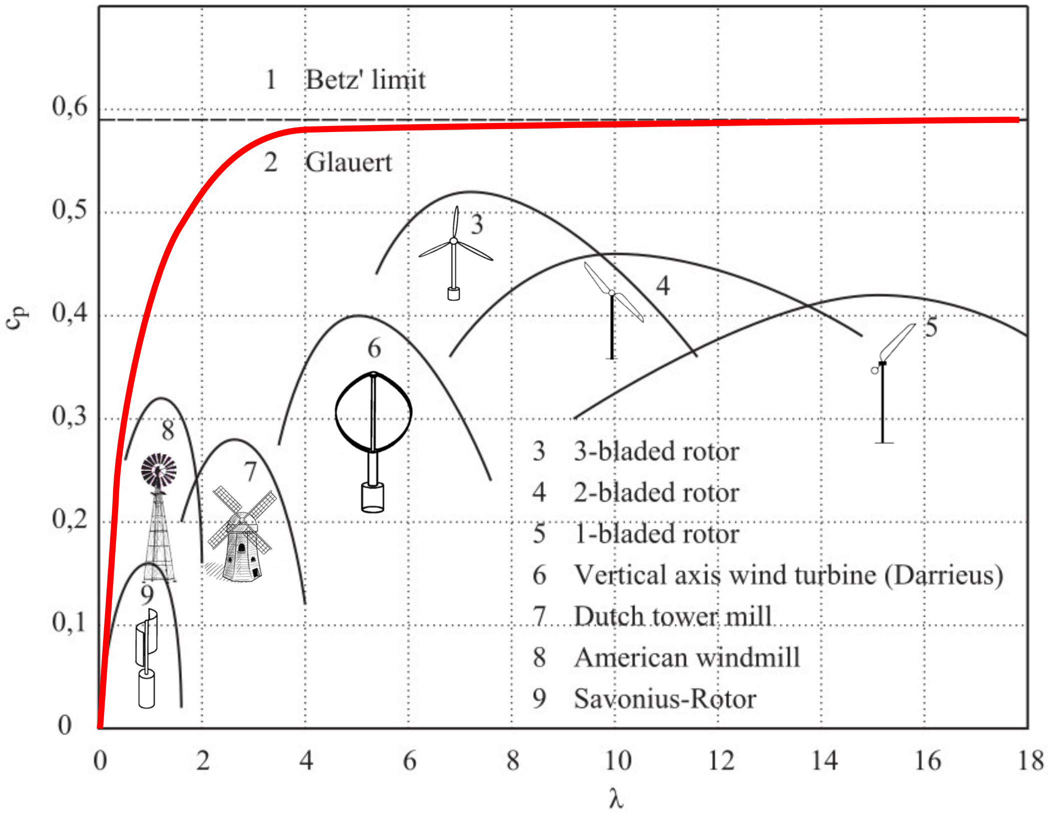
- Turbulence induces interaction between turbines
- Implies
  - Lateral spacing ~ 4 times radius
  - Longitudinal spacing ~ 7 times radius



Yield of various systems

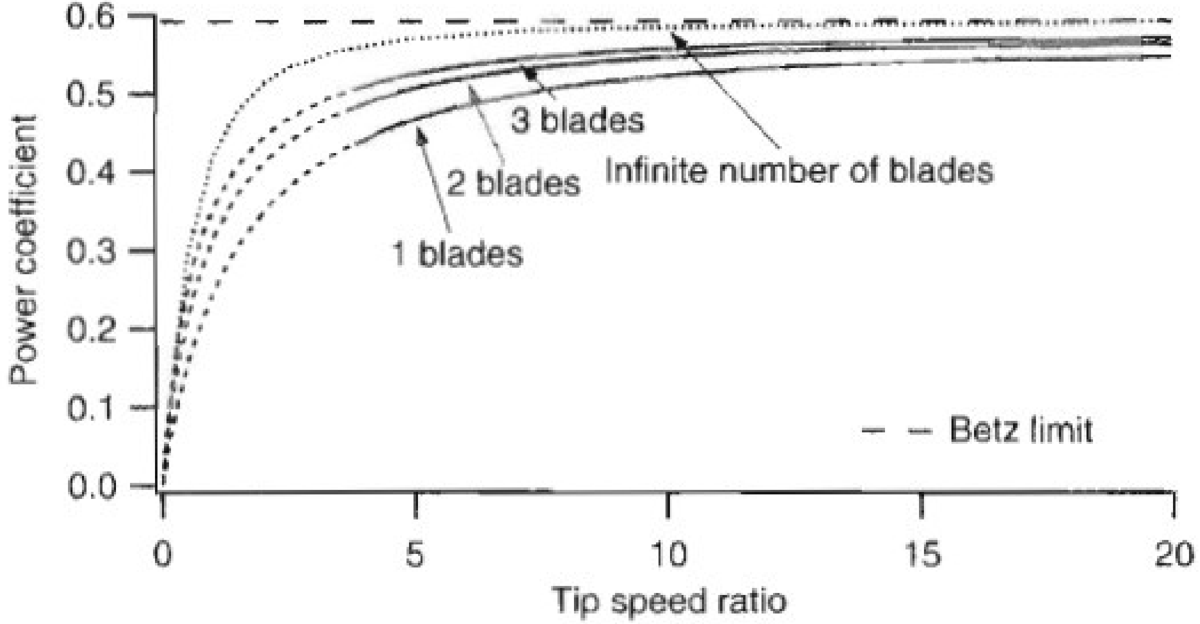
- Speed ratio at end of blades (tip-speed-ratio) :
  U: speed of the wind (far away)
  Ω: angular rotation speed
  R: blade length

$$\lambda = \frac{\Omega R}{U}$$

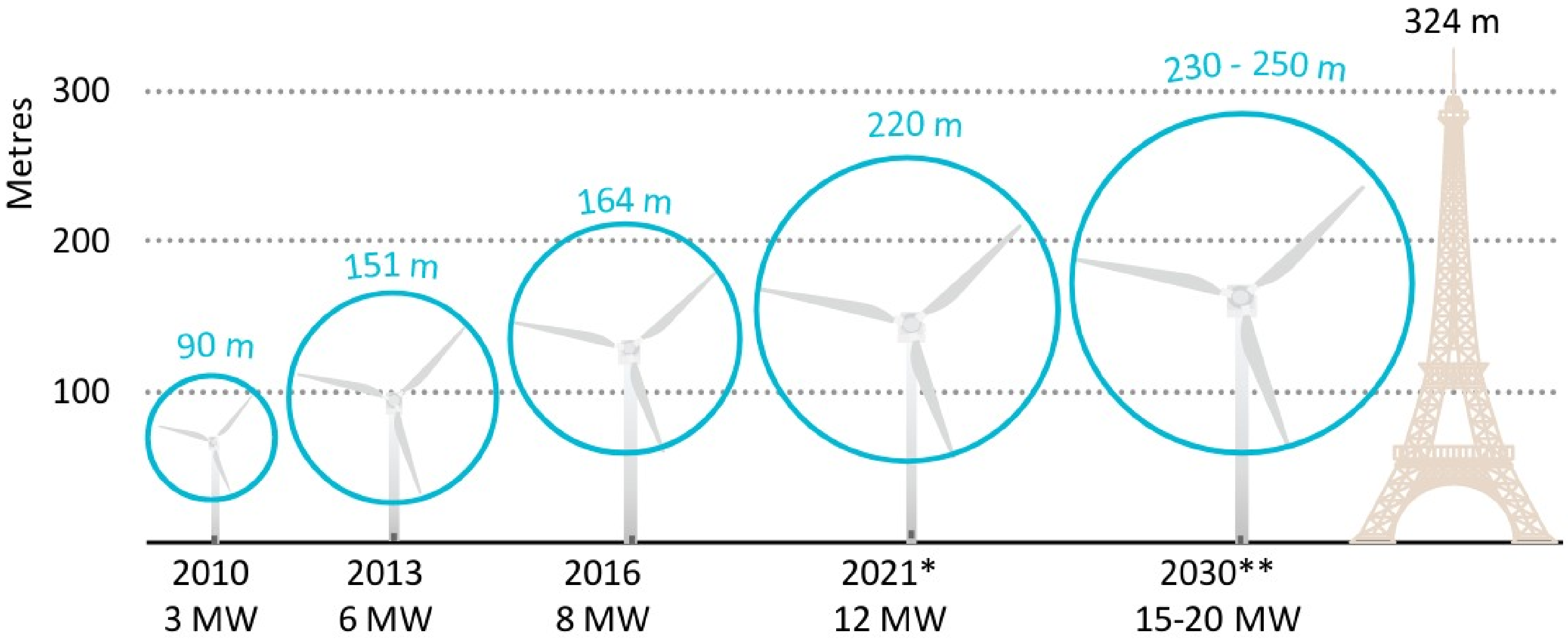


Yield of turbines

- 3 blades turbines tend to be the most efficient



Growing sizes



Technology advances enabled offshore wind turbines to become much bigger in just a few years and are supporting ongoing increases in scale

Large size Wind Turbines

Savonius Rotor

- Drag force driven
- Can operate on a large range of wind speeds
- Insensitive to wind direction

Darreius Rotor

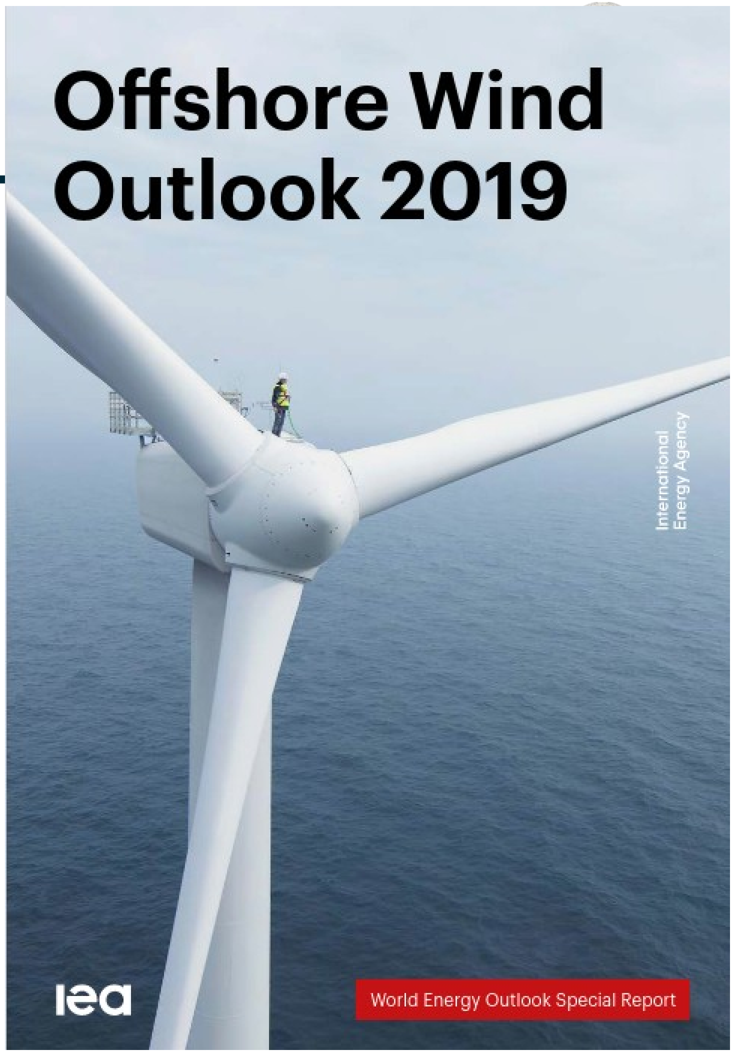
- Rotor spinning at a rate ~unrelated to wind speed
- Larger infrastructure cost (large fraction of the wing not effective)
- High centrifugal stress on the mechanisms
- Sinusoidal (pulsing) power that complicates design

Helical Darrieus Turbine

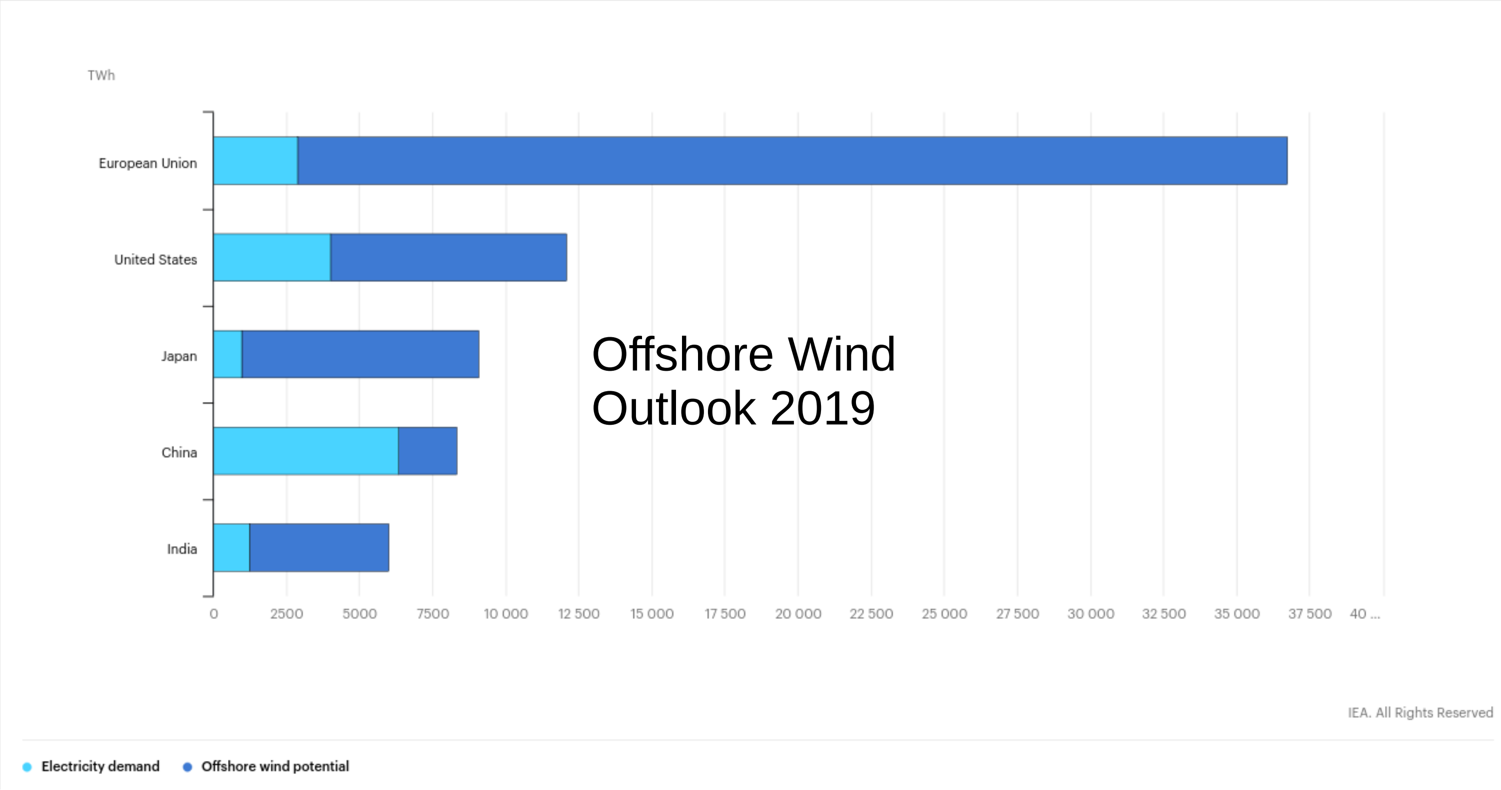
- Lightweight, more regular flow

Offshore wind potential

- Geospatial analysis by IEA (2019)
  - Potential: 36 000 TWh/yr (≤60 m deep, ≤60 km from shore)
    > global electricity demand (23 000 TWh/yr)
  - Floating turbine could supply ~11 times the world demand.
- Offshore wind is set to be competitive with fossil fuels within the next decade, as well as with other renewables including solar PV

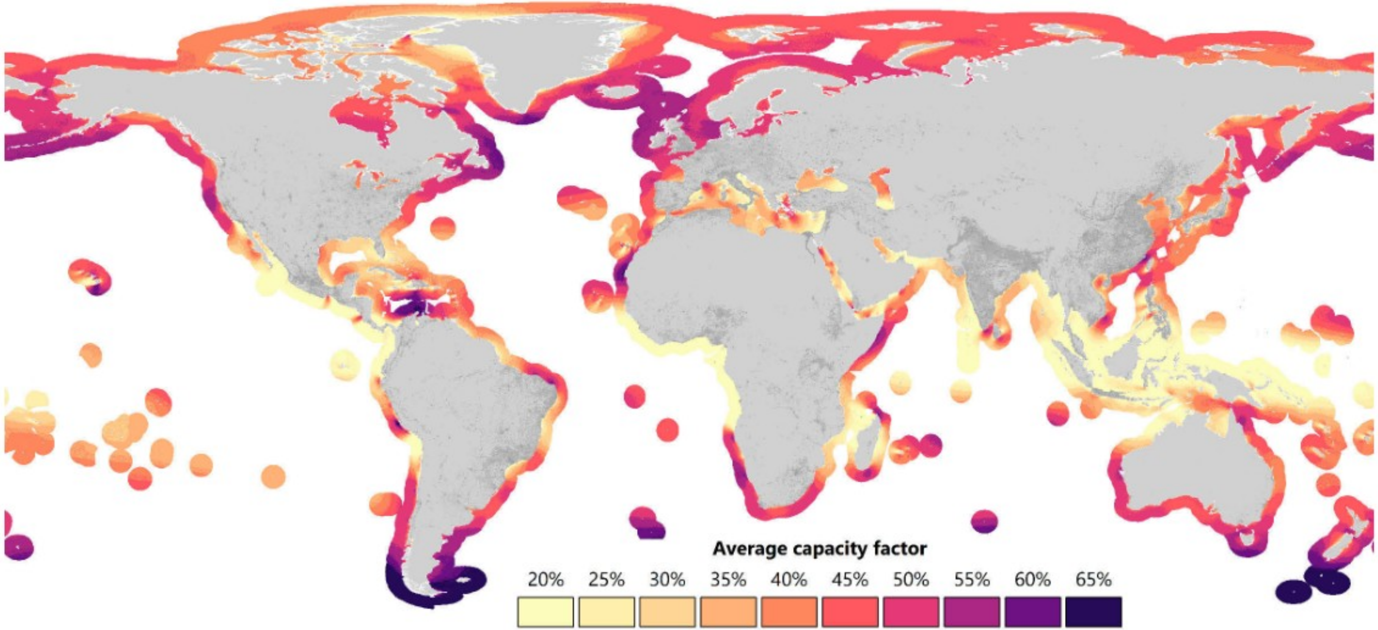


Offshore Wind Outlook



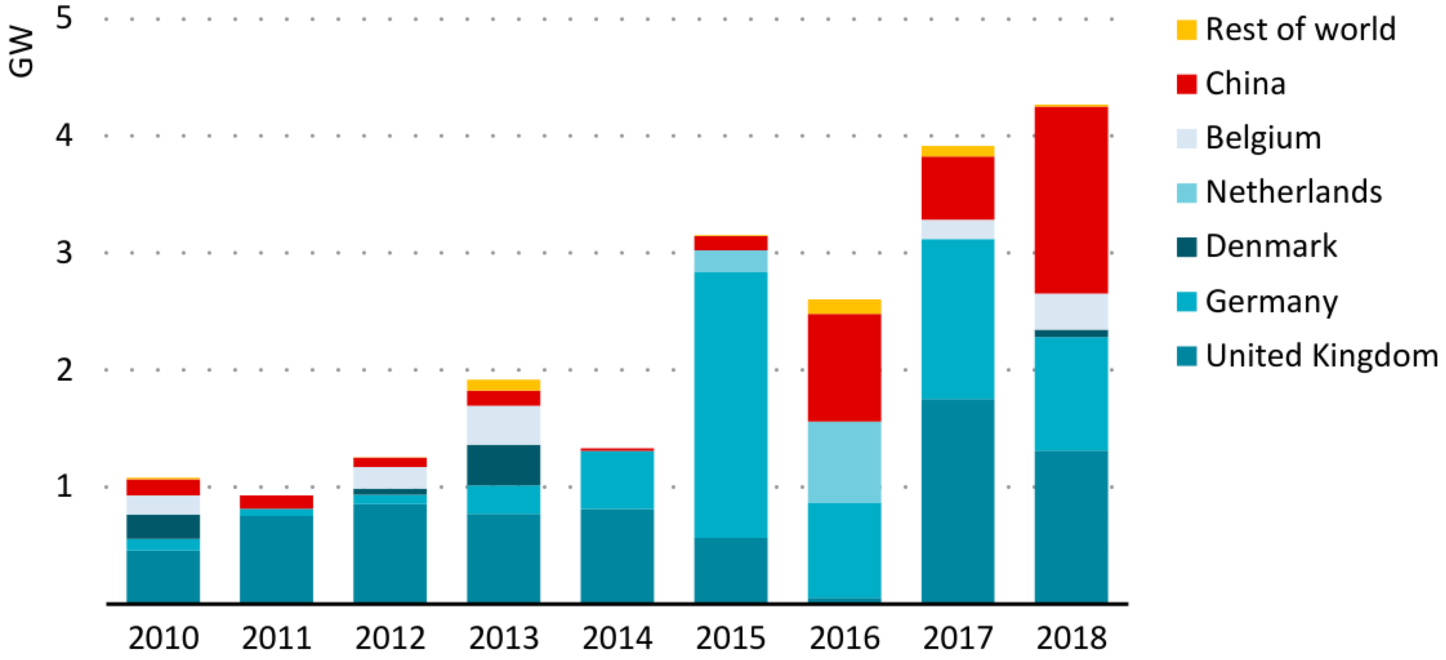
Offshore Wind Outlook 2019

Simulated capacity



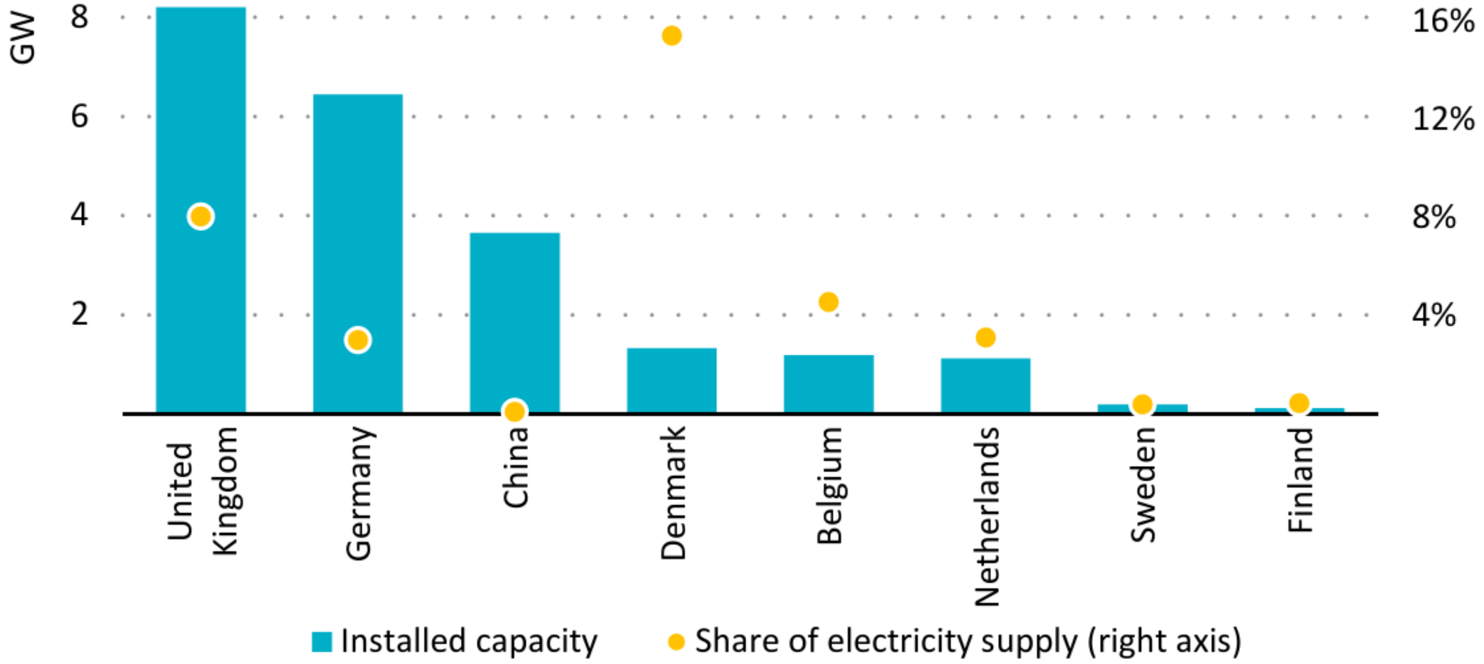
Average capacity factors reflect the quality of the wind resources available offshore around the world

Offshore Wind Growth



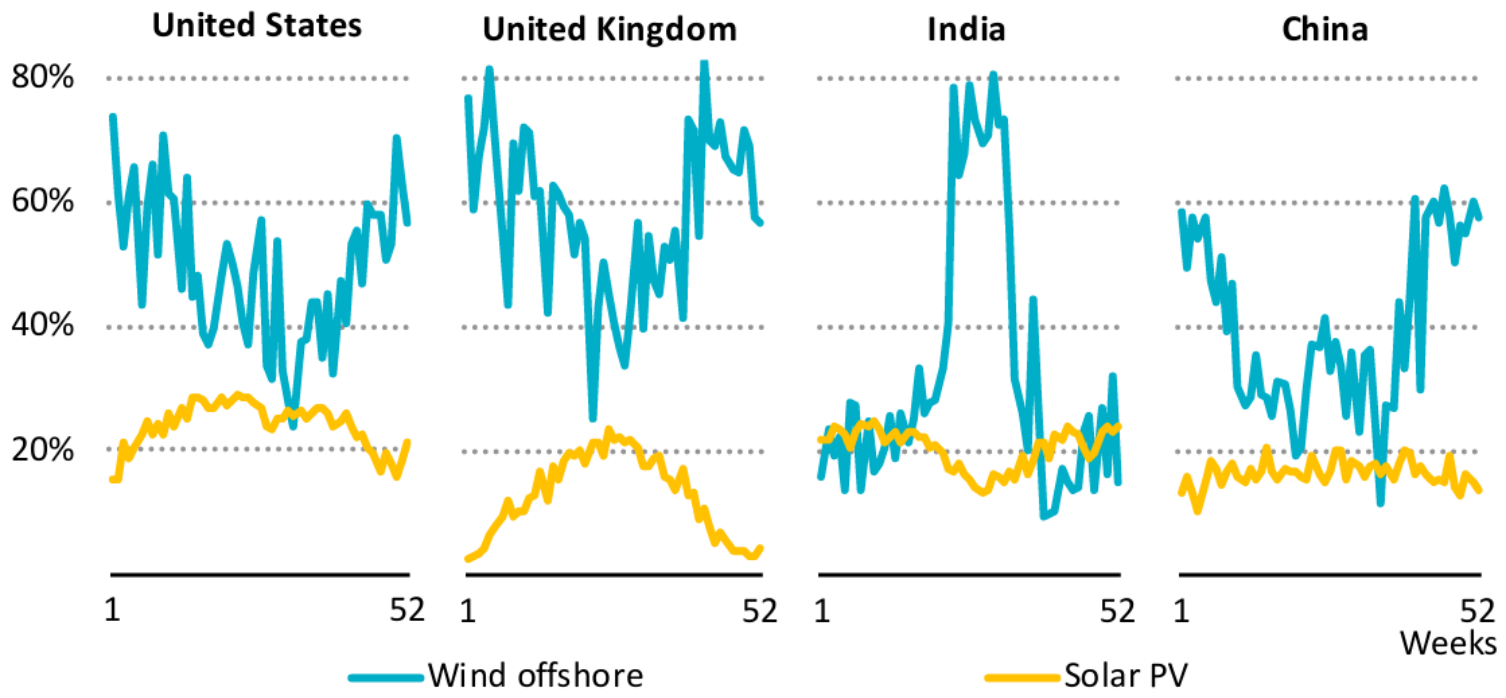
Deployment of offshore wind has increased by nearly 30% per year since 2010, second only to solar PV, as the technology and industry have matured

Installed capacity



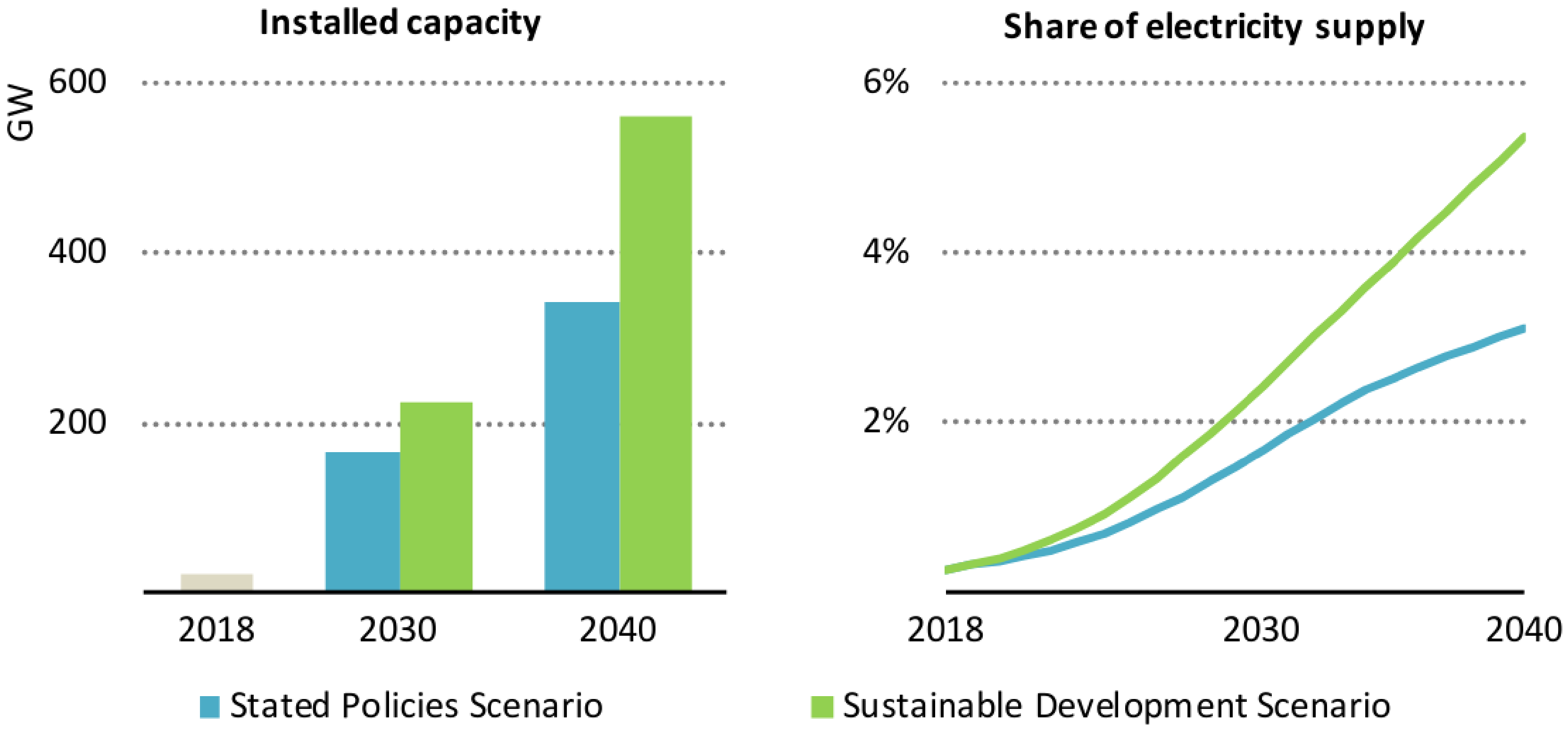
Most leading countries in offshore wind are in Europe, led by the United Kingdom, though China has quickly joined the top-three and is gaining momentum

Complementarity with PV

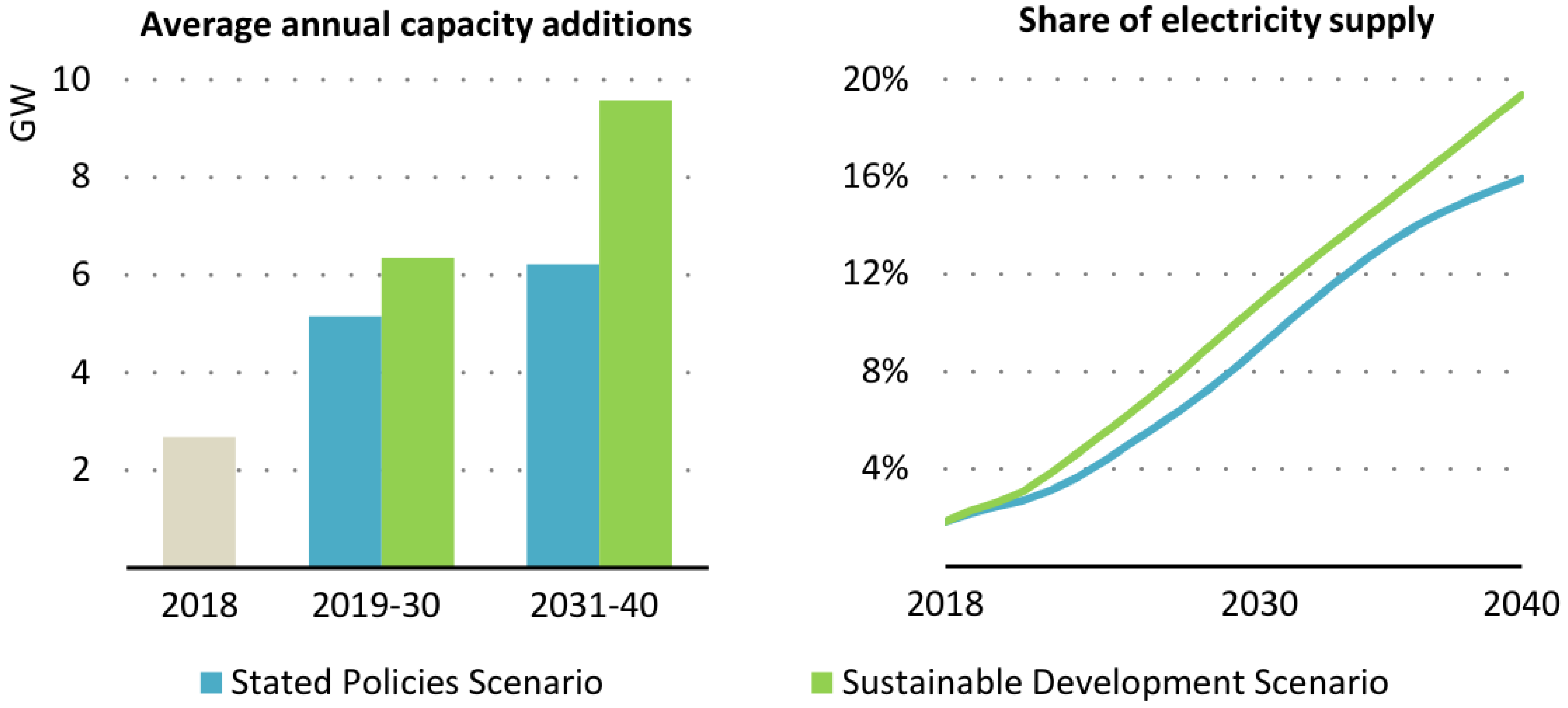


Seasonality of offshore wind can complement that of solar PV

Projected offshore wind capacity (world)



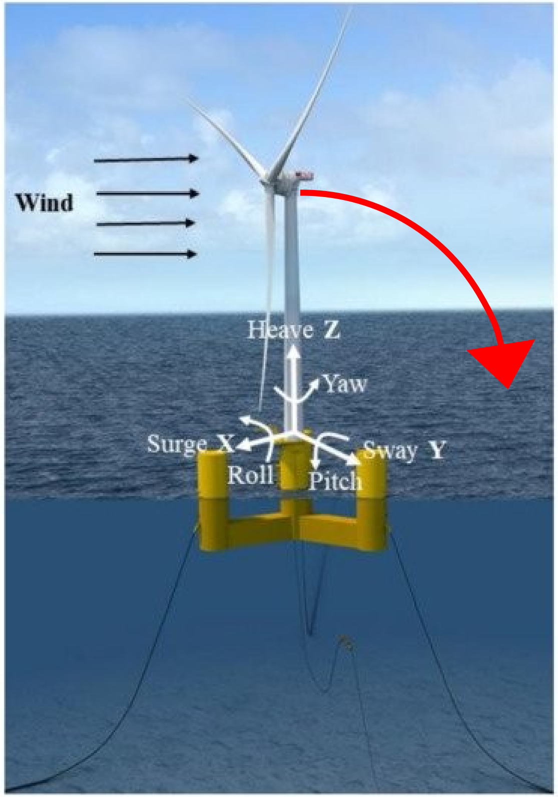
Europe


Average annual capacity additions
GW
10
8
6
4
2
2018
2019-30
2031-40
Share of electricity supply
20%
16%
12%
8%
4%
2018
2030
2040
Stated Policies Scenario
Sustainable Development Scenario

Challenges of floating wind turbines

- Wind thrust exerts a torque on the turbine mast
  ⇒ inclination + drift
  - 6 additional degrees of freedom:
    - 3 translational (surge X, sway Y, heave Z)
    - 3 rotational (roll X, pitch Y, yaw Z)

    + motion caused by waves
  - Need to be properly balanced!



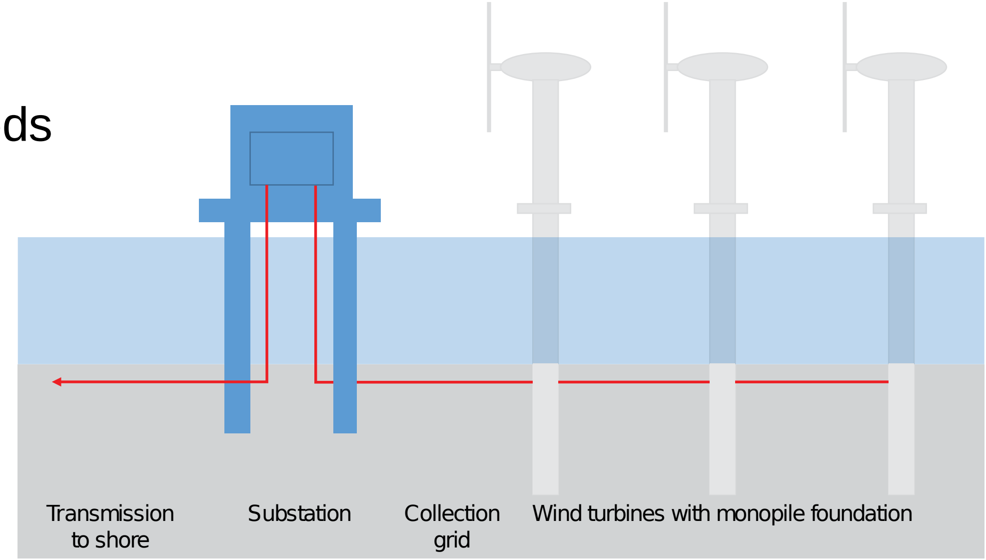
Floating wind turbines design

- Three main designs
  - Spar-buoy: long, weighted cylinder acting as balance ("Ballast Stabilized")
  - Semi-submersible platforms ("Buoyancy Stabilized")
  - Tension-leg structure with smaller platform anchored to the seabed with taut mooring lines ("Mooring Line Stabilized")

Semi-submersible floating wind turbines

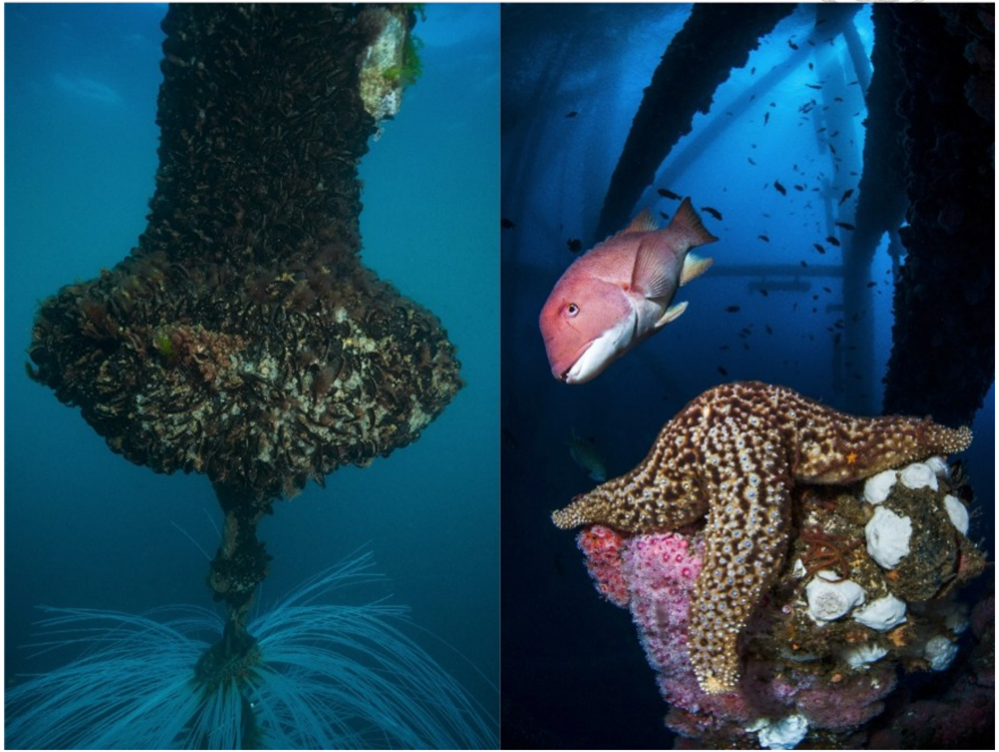
Connection to the grid

- Distant offshore wind farms use an internal grid (AC, ~33 kV) connected to a substation (⇒ transmission to shore, AC, ~150 kV)
- High Voltage DC current might be an option for shore connection (distances > 100 km)
- Other possibility: direct production of renewable hydrogen (avoid needs for transmission)



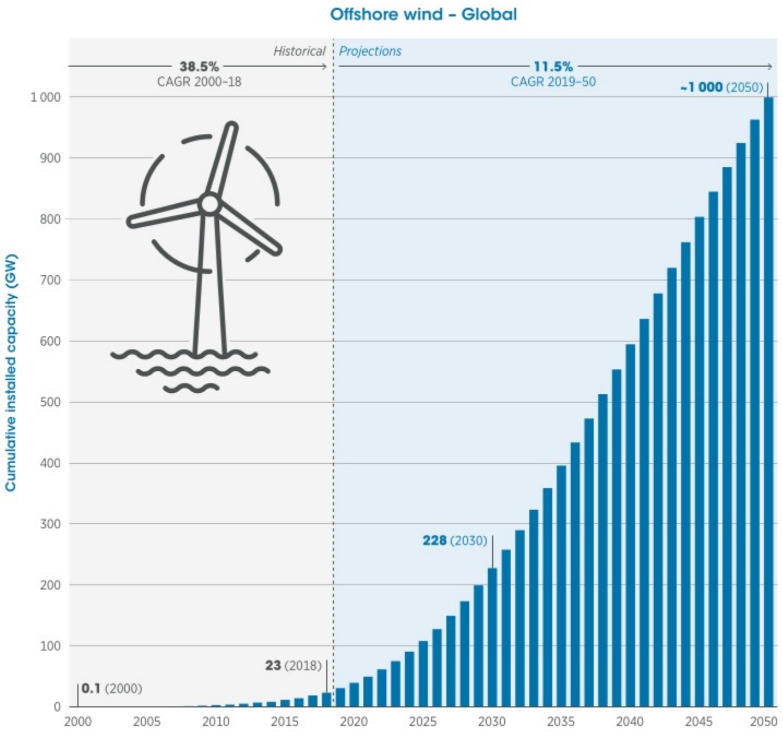
Environmental Impact

- Currently quite not clear:
  - ☹ Impact of foundations (concrete), cable path, etc.
  - ☺ Artificial reef, creation of new living area for shells and subsequently for fishes
- To be considered in design



Projections

- “Offshore wind power deployment would grow gradually to nearly 1 000 GW of total installed capacity by 2050.”
(IRENA, “Future of Wind, 2019)



Source: Historical values based on IRENA's renewable capacity statistics (IRENA, 2019d), future projections based on IRENA's analysis (IRENA, 2019a).

Lecture 7 – Wind & Hydro Energies

I. Hydraulic energy

II. Wind Resources

III. Betz Limit

IV. Basics of aerodynamics

V. Wind Turbines

VI. Submarine turbines & tidal energy

VII. Conclusions & Outlook

Marine Turbines

- Marine Turbines: higher density (×1000), current steadier but less intense, predictable (tidal)

Energy range

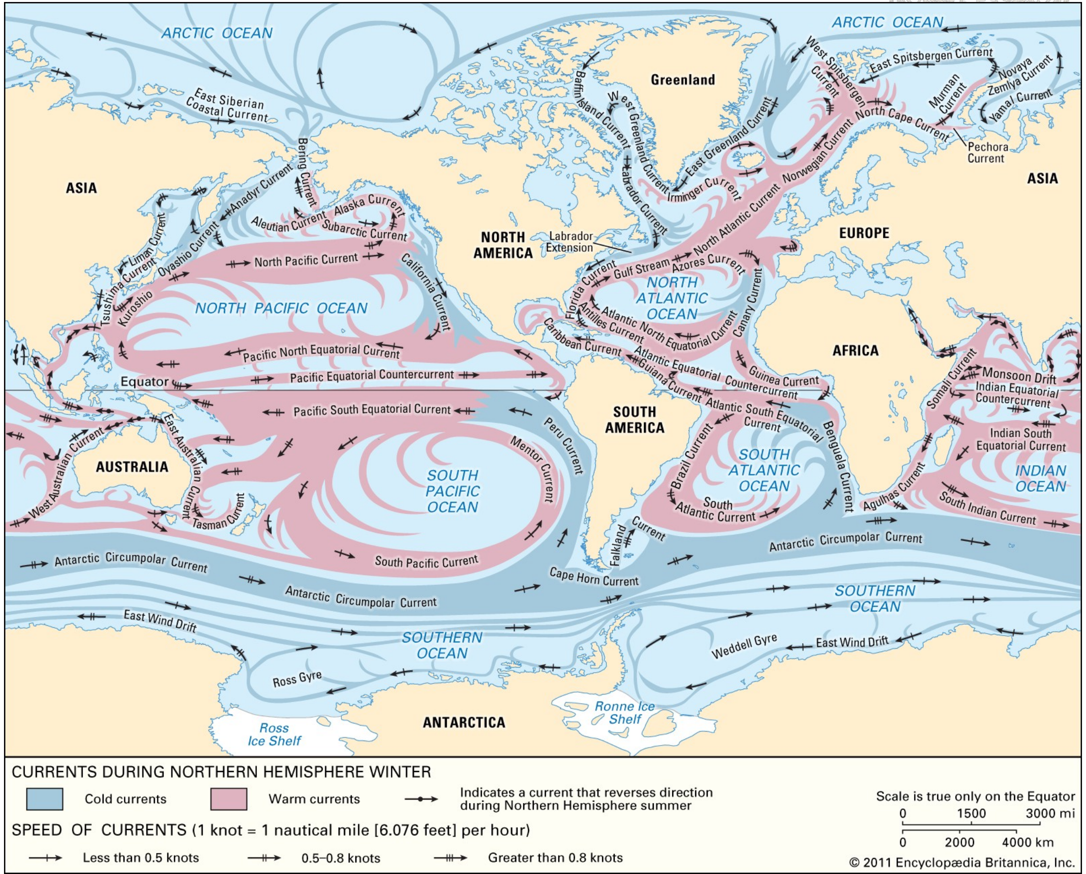
- Power $$P=\frac{1}{2}\rho v^{3} S$$

Speed (m/s)	Power Density (W/m²)
1	8
2	60
3	200
4	500
5	1000

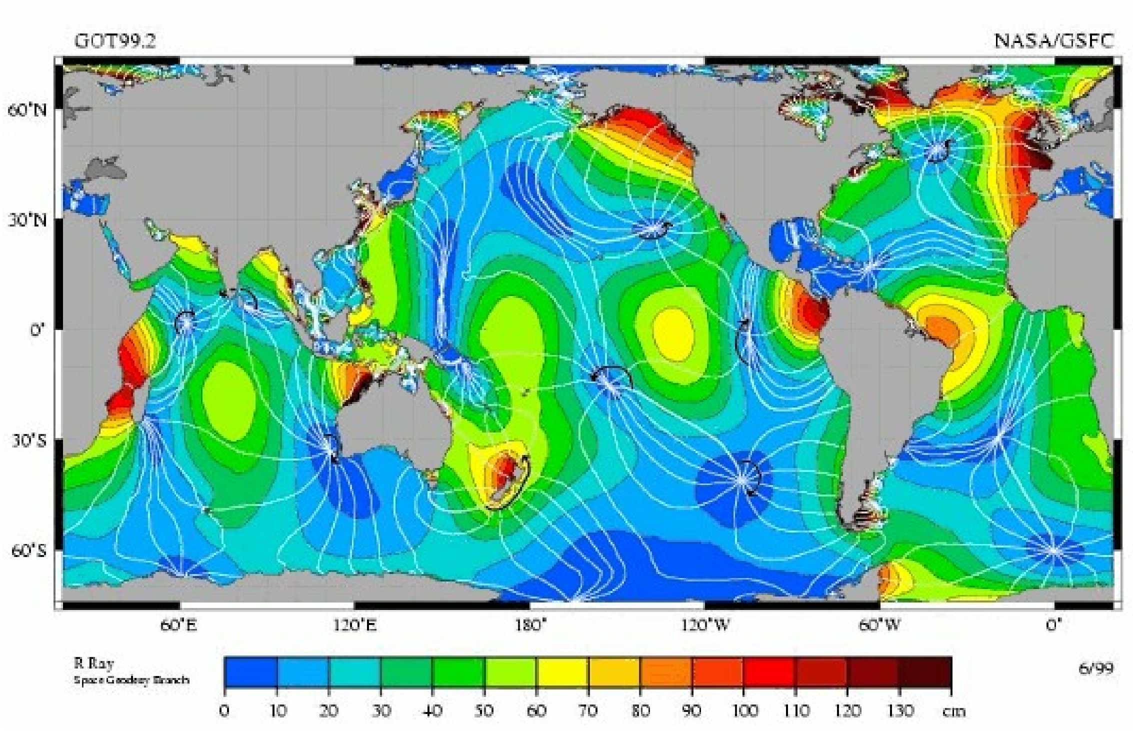
https://
www.withouthotair.com

Steady currents

- Typical velocities ~1 m/s
- Power in Gulf Stream ~ 50 GW
- << tidal currents!

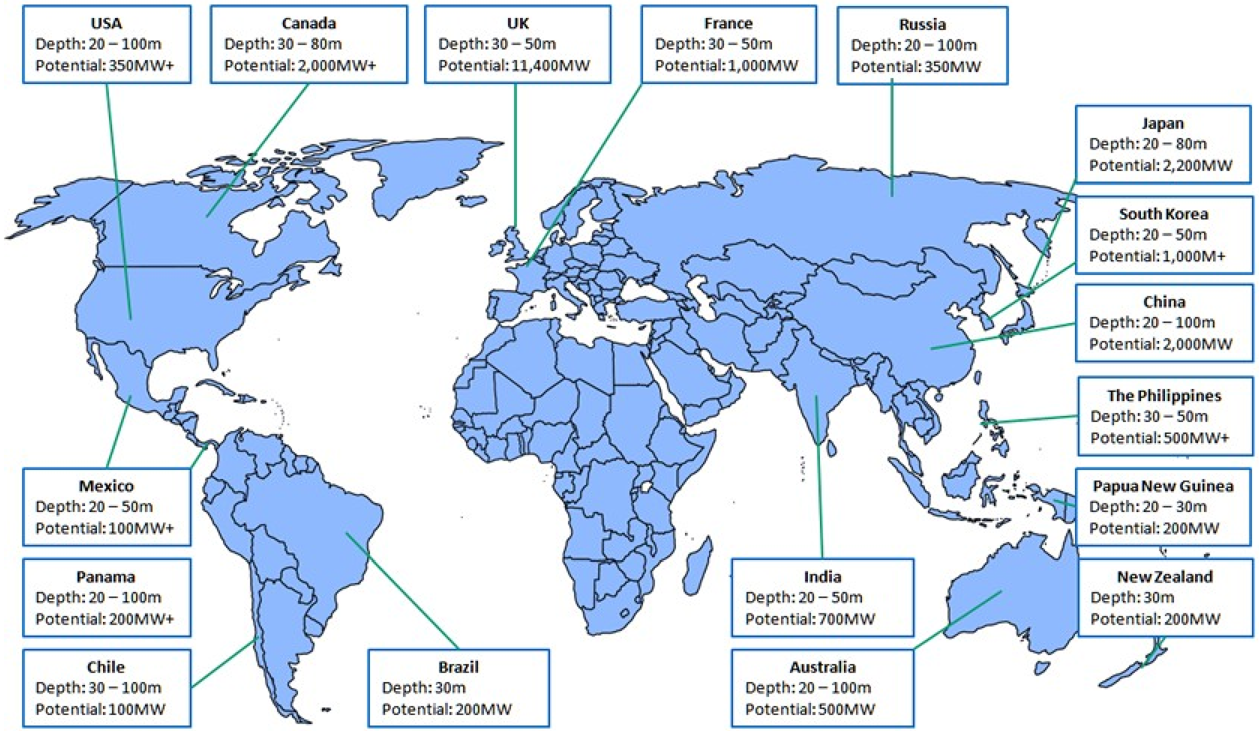


Tidal amplitude



The lunar tidal component as measured by the U.S./French satellite TOPEX/Poseidon.

Tidal potential



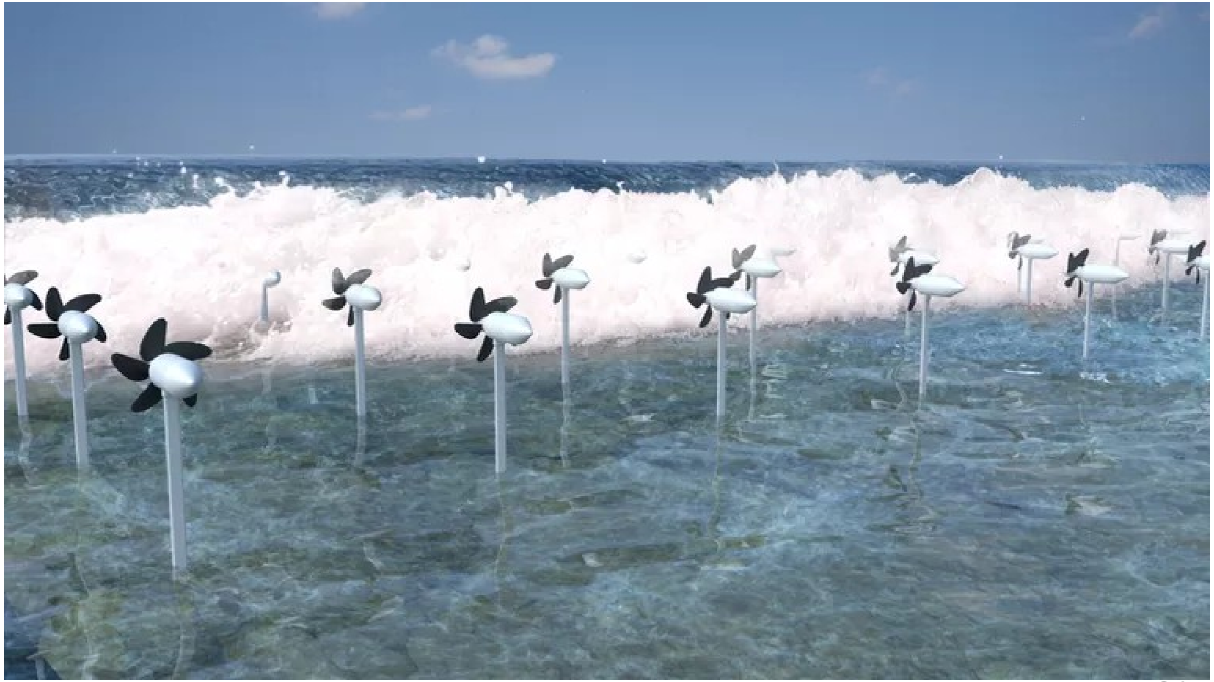
Global tidal stream resource (Atlantis, n.d.)

Marine Turbines

- Similar design to wind turbines, but smaller sizes

Wave Turbines

- Reduce strength of crashing waves and produces energy



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Take-home message

- Hydroelectric energy is saturating in developed countries
- Wind energy is a mature technology, becoming continuously cheaper
- Expected to play a significant role in energy transition
- Off-shore is very promising (more regular, stronger winds) but some challenges
- Pumped storage important to mitigate transient aspects of wind energy
- Submarine turbines may be further developed