Wind Energy Fundamentals

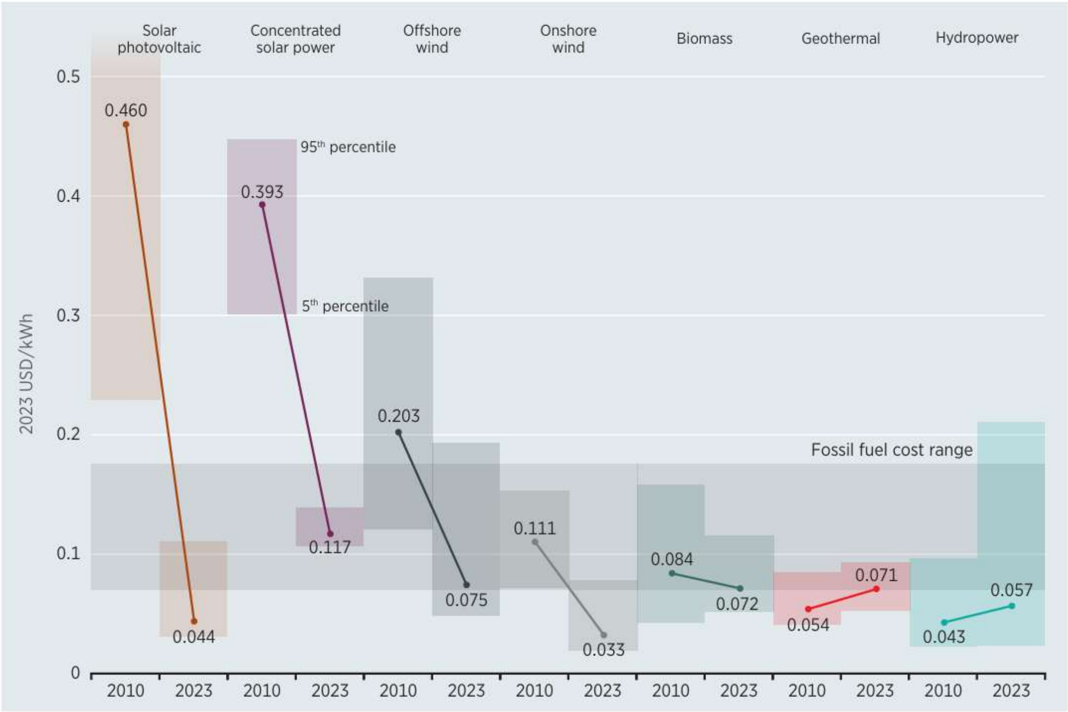
Lecture - Learning Objectives

At the end of this lecture you should be able to:

- Understand the thermodynamic limit for wind energy
- Understand how thrust occurs and tip-speed ratio
- Understand the interworkings of a wind turbine

Wind Energy - Overview

- Offshore wind is becoming economically viable
- Offshore wind is non-invasive to people and much more consistent

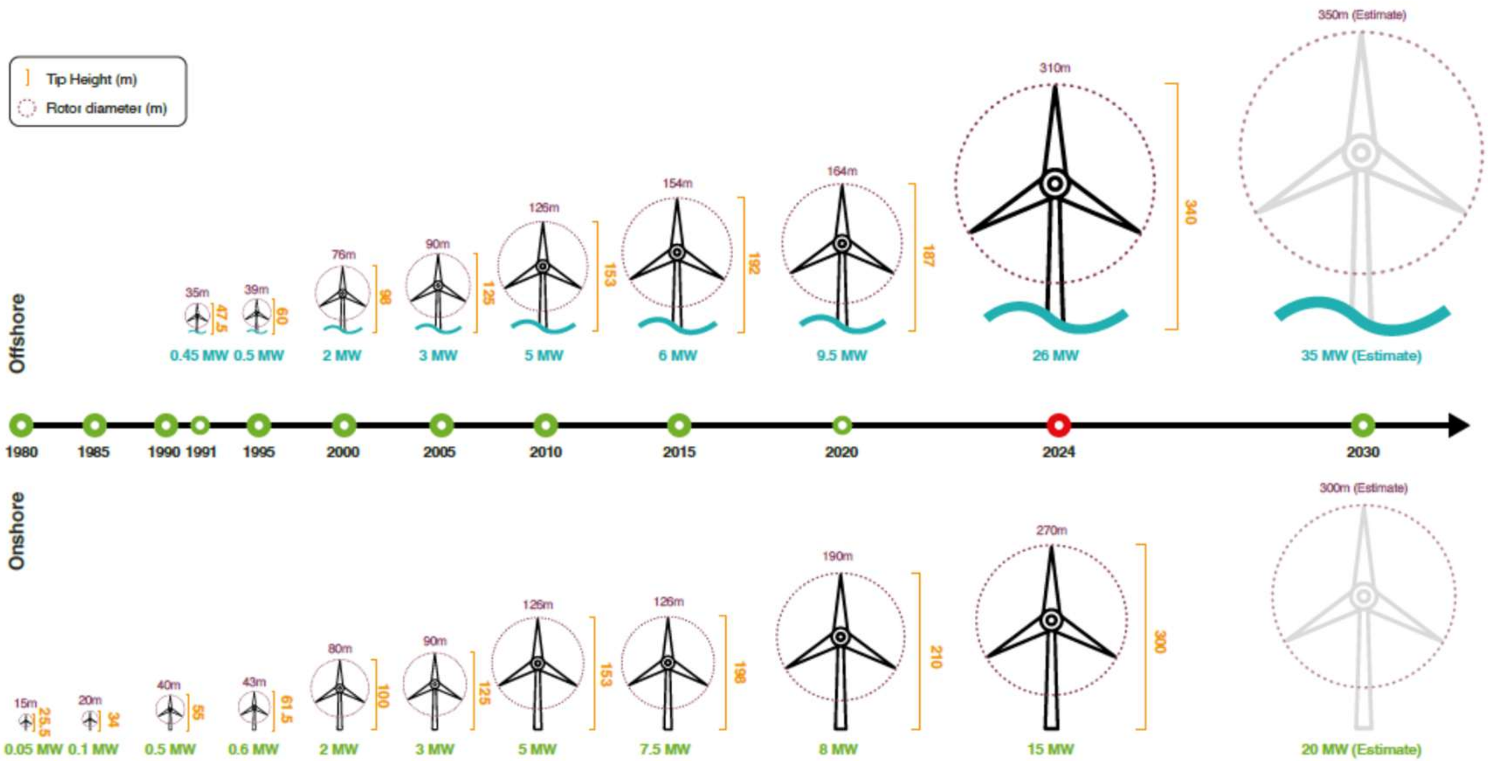


IRENA Renewable Power Generation costs report, 2023

Wind Energy - Overview

- Offshore wind favors larger wind turbines

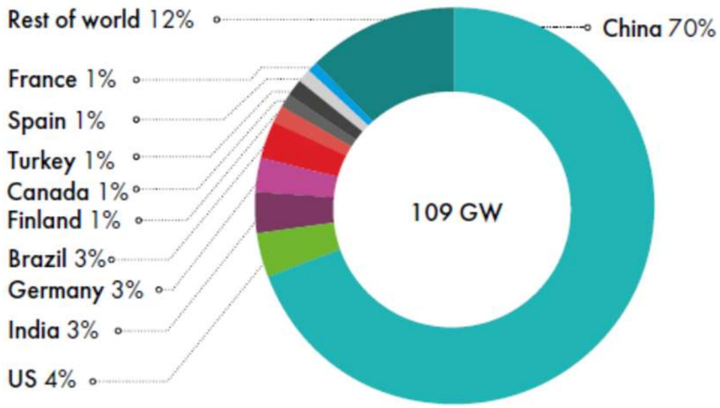
Trend of onshore and offshore turbine size, 1980-2030



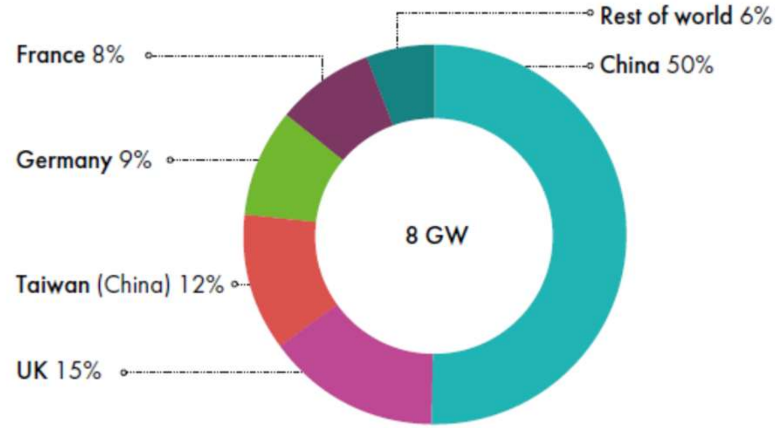
Source: GWEC Market Intelligence.

GWEC- Global Wind Energy Report 2025

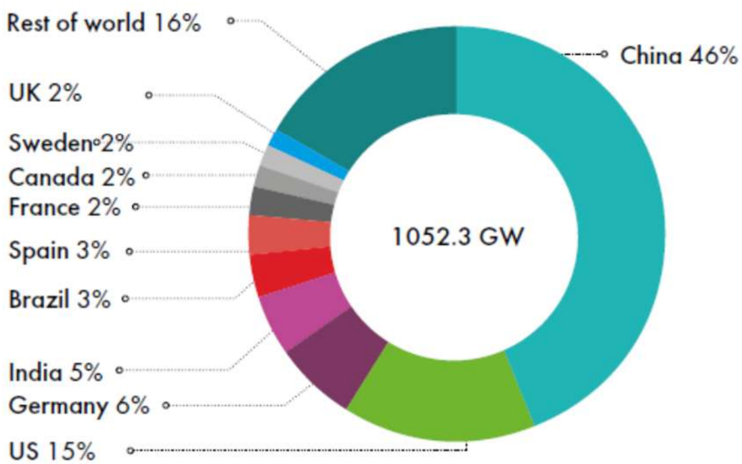
New installations onshore (%)



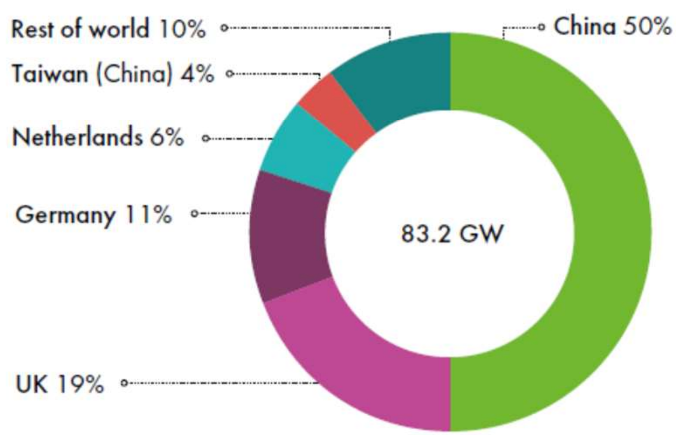
New installations offshore (%)



Total installations onshore (%)



Total installations offshore (%)



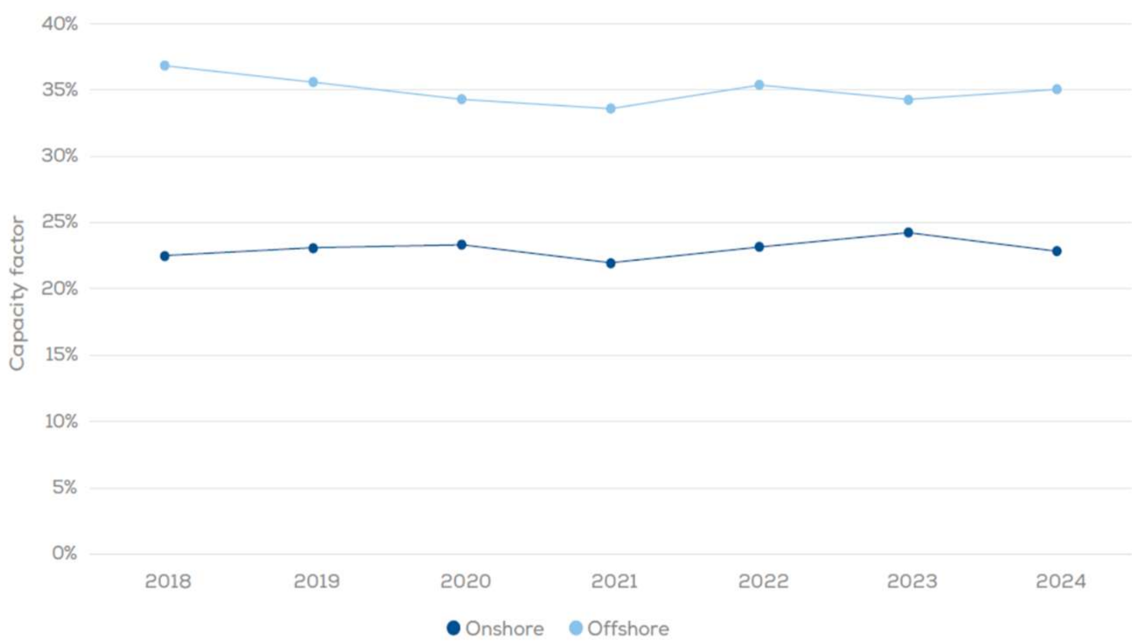
Detailed data sheet available in GWEC's member-only area. For definition of region see Appendix - Methodology and Terminology

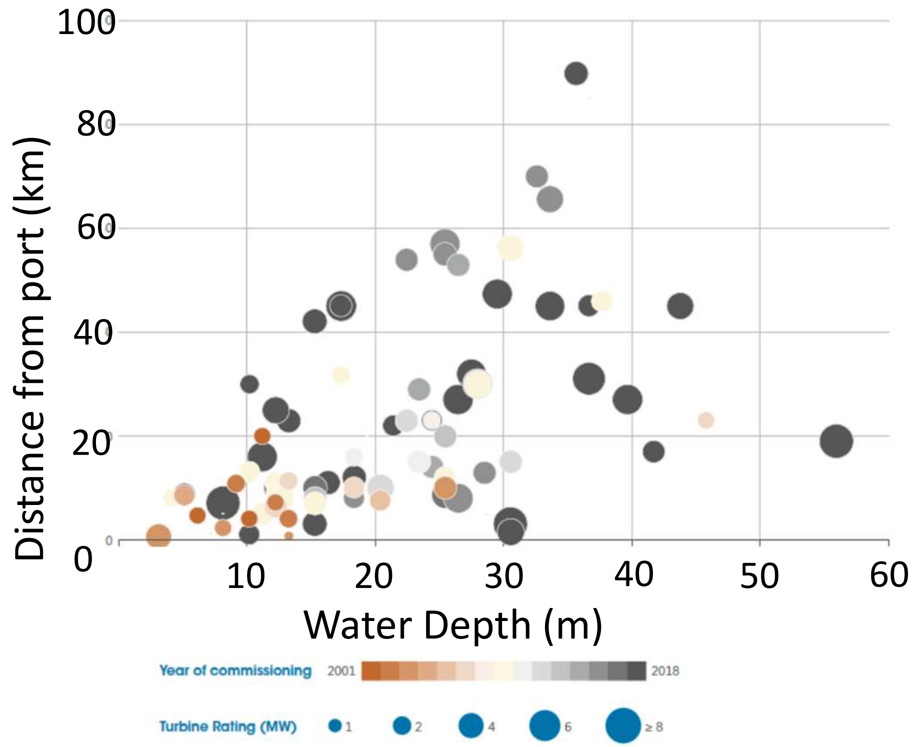
GWEC- Global Wind Energy Report 2025

Wind Energy - Overview

- While offshore wind is more expensive, its capacity factor is much better

FIGURE 17. Average capacity factor of installed wind turbines in the EU, 2018-24





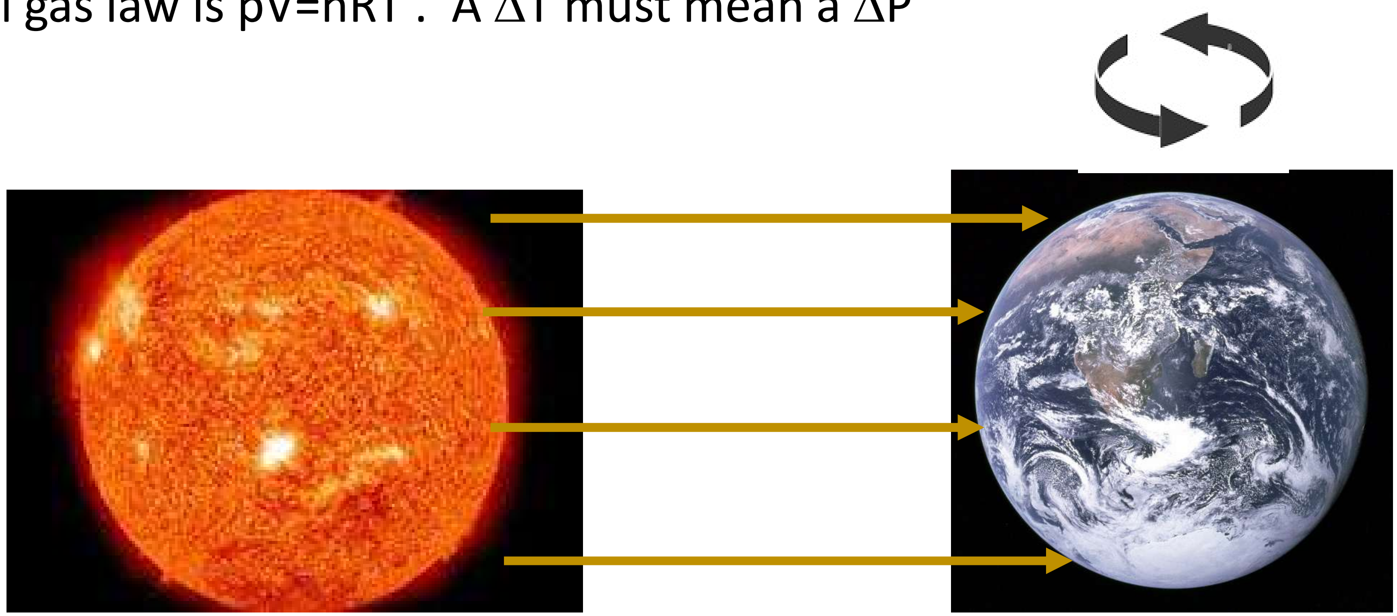
DOI:[10.3390/jmse7120441](https://doi.org/10.3390/jmse7120441)

Physics behind wind energy

Why does wind occur ?

- The earth heats different places at different rates
  - Equator gets more sunlight than the poles
  - The rotation of the earth is faster at the equator than the poles effecting heating rates
  - Water acts as a heat sink, moderating temperatures.
  - etc.

- Ideal gas law is pV=nRT . A ΔT must mean a ΔP



Power

E = Energy
m = mass
v = velocity
P = power
T = time
S = area

- How much power does wind provide.
- Lets break this down as followed:

$$E = {}^{1}/_{2}\, mv^2$$ ← Eqn for kinetic energy

$$P = \frac{\Delta E}{\Delta t} = \frac{\Delta {}^{1}/_{2} mv^2}{\Delta t} = {}^{1}/_{2}\, \dot{m} v^2 = {}^{1}/_{2}\, (S\rho v) v^2$$

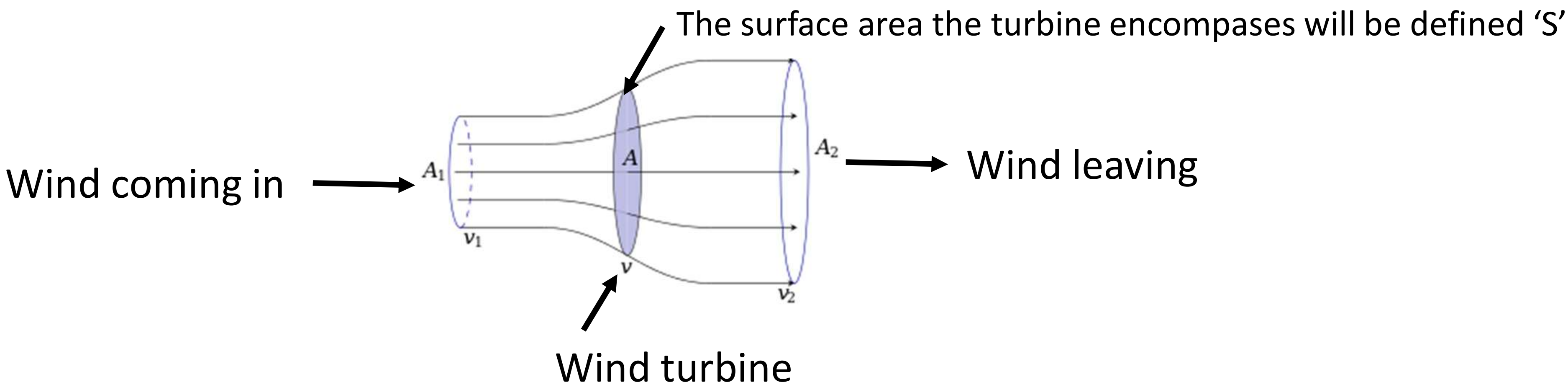
↑ Mass flow rate

$$P_{wind} = {}^{1}/_{2}\, S\rho v^3$$

- Power scales with velocity to the 3rd power. (Due to practical losses though this scaling is typically a bit less than to the 3rd power)
- Now that we know how much power wind provides is there a limit to how much of this we can obtain? (hint: The answer is yes)

Power from Wind Turbines

- The total energy from the wind assumes the wind molecules come to a complete stop.
- We need to get rid of the stopped wind molecules, thus we need some velocity to remove them.
- This means that the wind after the turbine (S_2, V_2) will have a smaller, yet significant wind velocity than the incoming wind (S_1, V_1) .



Wind Power from Turbines

- From kinetic energy we know :

$$E = {}^{1}/_{2}\, m v^2$$

Different wind velocity before and after wind turbine

$$\Delta E = {}^{1}/_{2}\, m (v_1^2 - v_2^2)$$

Mass flow rate

$$P = \frac{\Delta E}{\Delta t} = {}^{1}/_{2} \frac{m}{\Delta t} (v_1^2 - v_2^2)$$

$$P = \frac{\Delta E}{\Delta t} = {}^{1}/_{2}\, \rho S v_{@T} (v_1^2 - v_2^2)$$

- In this approach we determined the power from an energy balance.
- We can also calculate the power using a force balance

Wind Power via Newton's 2nd Law

- If we denote force from wind as:

Mass flow rate

$$F = ma = m * \frac{dv}{dt} = \frac{m}{\Delta t}\Delta v = \dot{m}\Delta v = \rho S v_{@T}(v_1 - v_2)$$

The change in energy occurs at the turbine blade (i.e. @T)

$$P = \frac{dE}{dt} = \frac{d(F * x)}{dt} = F * \frac{dx}{dt} = \rho S v_{@T}(v_1 - v_2) * v_{@T} = \rho S v_{@T}^2(v_1 - v_2)$$

- This is strange. Using a kinetic energy approach and a force balance approach both gives us power equations.

Energy Balance vs Force Balance

- From kinetic energy we know our turbine power is: $P = {}^{1}/_{2}\, \rho S v_{@T}(v_1^2 - v_2^2)$
- From force balance we know our turbine power is: $P = \rho S v_{@T}^2 (v_1 - v_2)$
- What this tells us is that v_1, v_2 and $v_{@T}$ are inter-related. If we set 2 of these values the third one will be automatically set.
- If we set our energy balance equation equal to our force balance and solve for $v_{@T}$ we get:

$$ {}^{1}/_{2}\, \rho S v_{@T}(v_1^2 - v_2^2) = \rho S v_{@T}^2 (v_1 - v_2) $$

⬇ Boring algebra

$$ v_{@T} = {}^{1}/_{2}\, (v_2 + v_1) $$

Maximum Wind Power

- From kinetic energy we know : $P = {}^{1}/_{2}\, \rho S v_{@T} (v_1^2 - v_2^2)$

  or

  $P = {}^{1}/_{4}\, \rho S (v_2 + v_1)(v_1^2 - v_2^2)$

- Now we know what $v_{@T}$ is, however we have to figure out what our maximum power can be.
- However what we really are interested in is the ratio of v_2 to v_1 and thus we should take our derivative with respect to that.
- First we need to get P in terms of v_2/v_1. After a bit of algebra we get:

$$P = {}^{1}/_{4}\, \rho S v_1^3 \left(-\left(\frac{v_2}{v_1}\right)^3 - \left(\frac{v_2}{v_1}\right)^2 + \frac{v_2}{v_1} + 1 \right)$$

Maximum Wind Power

- We need to take the derivative of : $P = {}^{1}/_{4}\,\rho S v_1^3 \left(-\left(\frac{v_2}{v_1}\right)^3 - \left(\frac{v_2}{v_1}\right)^2 + \frac{v_2}{v_1} + 1 \right)$ and set it equal to zero

- Thus $\dfrac{dP}{d\left(\frac{v_2}{v_1}\right)} = 0 \quad \Longrightarrow \quad \dfrac{v_2}{v_1} = {}^{1}/_{3}$

- And thus the max power from our wind turbine is:

$$P = {}^{1}/_{4}\,\rho S v_1^3 \left(-\left(\frac{v_2}{v_1}\right)^3 - \left(\frac{v_2}{v_1}\right)^2 + \frac{v_2}{v_1} + 1 \right) = {}^{16}/_{27} \times {}^{1}/_{2}\,\rho S v_1^3$$

Another way to look at things

- If the maximum wind turbine power is : $P_{Turbine} = {}^{16}/_{27} \times {}^{1}/_{2}\, \rho S v_1^3$

- And the total power from the incoming wind is: $P_{Wind} = {}^{1}/_{2}\, \rho S v_1^3$

- Thus : $\frac{P_{Turbine}}{P_{Wind}} = \frac{{}^{16}/_{27} \times {}^{1}/_{2}\, \rho S v_1^3}{{}^{1}/_{2}\, \rho S v_1^3} = {}^{16}/_{27} = 59\%$

- Thus the maximum efficiency is 16/27 (or 59%), which is called the Betz Limit.

Maximum Wind Power

Instead of this diagram, we can use this diagram

Figure A

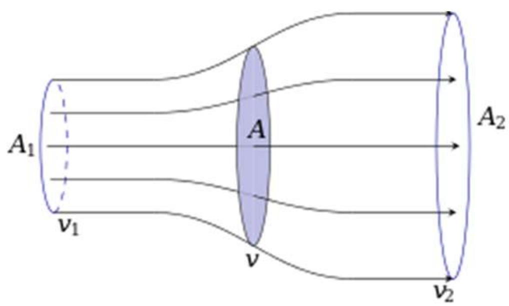
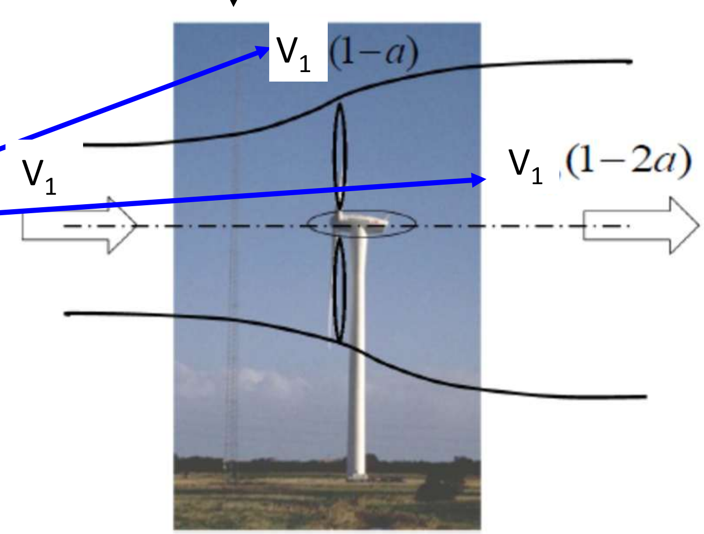


Figure B



These ratios are true because of what we derived earlier:

$v_{@A} = {}^{1}/_{2}\,(v_2 + v_1)$

Axial interference cofactor ⟶ $a = 1 - \frac{v_{@T}}{V_1}$ ⟵ *v*= velocity at wind turbine

$a_{max} = {}^{1}/_{3}$

Coefficient of performance

- Our coefficient of performance (C_p) is simply:

$$C_p = \frac{P_{Turbine}}{P_{Wind}}$$

Terminology from Figure A of previous slide

$$= \frac{\rho S v_{@T}^2 (v_1 - v_2)}{{}^1\!/_2\, \rho S V_1^3}$$

Terminology from Figure B of previous slide

$$= \frac{\rho S \left({}^1\!/_2\,(v_2 + v_1)\right)^2 (v_1(1-2a) - v_1)}{{}^1\!/_2\, \rho S V_1^3}$$

Boring Algebra

$$C_p = 4a(1-a)^2$$

- If *a*=1/3 C_p will be 59%, but any other *a* will yield a different C_p.

Pressure drop across blades

- Bernouilli's equation lets us link pressure to velocity

$$p_1 + {}^1/_2\, \rho v_1^2 = p_2 + {}^1/_2\, \rho v_2^2$$

- By isolating pressure difference we get:

$$\Delta p = \frac{\rho}{2}(v_1^2 - v_2^2)$$

- Or in terms of 'a':

$$\Delta p = 2\rho v_1^2 a(1 - a)$$

Thrust

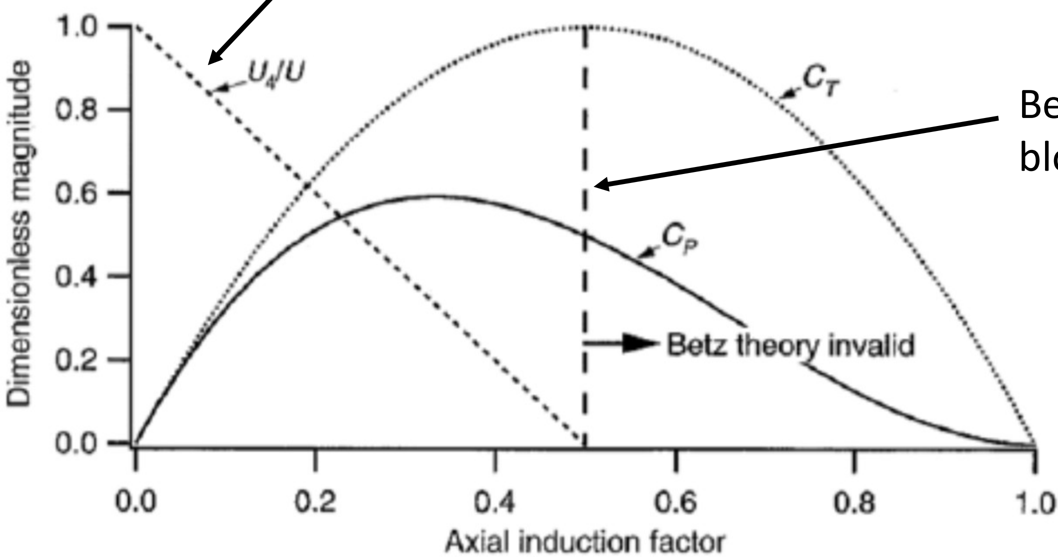
- We can relate pressure to thrust via a basic physics equation: $T = S\Delta p$
- If we use our Bernoulli equation result for pressure we get $T = 2S\rho v_1^2 a(1-a)$
- Maximum thrust is when v_2=0, thus: $T_{Max} = \frac{S\rho}{2} v_{Max}^2$
- We can create a 'Coefficient of Thrust' as follows:

$$C_T = \frac{\text{Thrust Force}}{\text{Maximum Force from wind}} = \frac{2s\rho v_1^2 a(1-a)}{\frac{S\rho}{2} v_1^2} = 4a(1-a)$$

Optimal Thrust Coefficient

- The optimal C_T is 8/9.
- The table below plots C_P and C_T as a function of *a*

Outgoing wind /Incoming wind



Beyond this point the wind is blowing backwards

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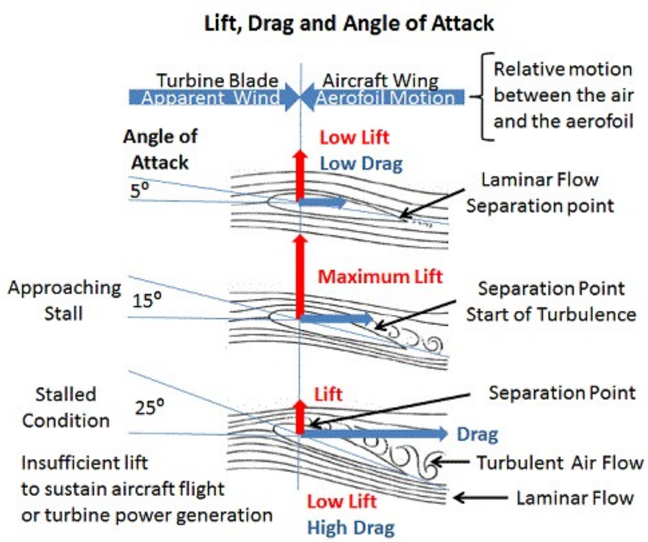
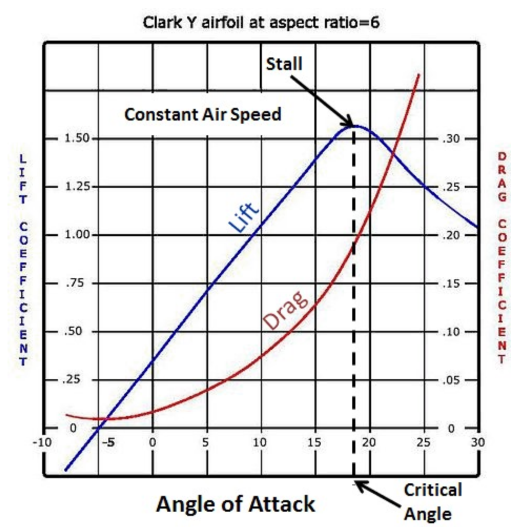
How do we get a presure difference across the blade?

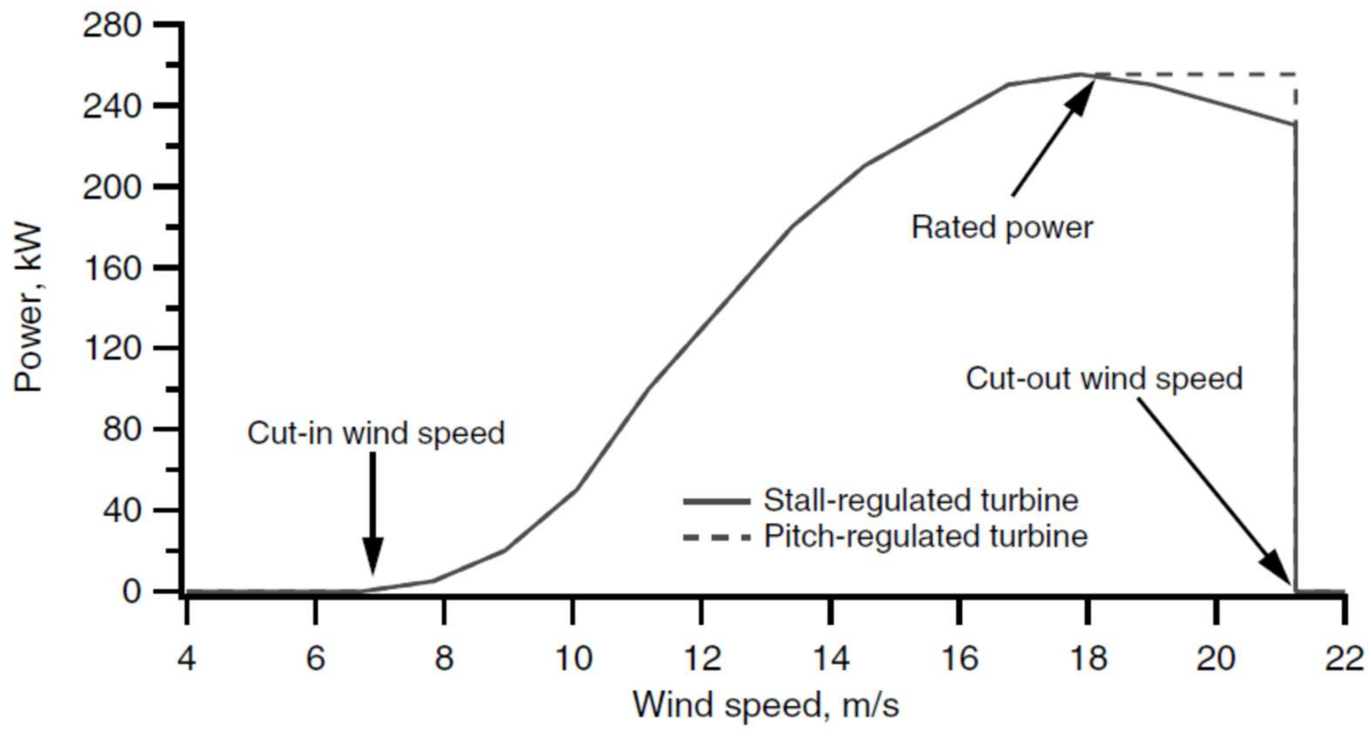
- The blade is designed so it forces the wind to have a lower pressure on one side that so it gives the blade 'Lift'
- The key is mitigating turbulence, because this creates 'Drag'.
- Beyond a certain angle the turbulence reaches the lift point, and drastically decreases lift.
  - This is called 'Stall'

[Airflow across a wing (youtube.com)]





Realistic power curve for wind turbine



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Looking at Angular Velocity

- We can use Bernoulli's Equation to look at force balance at the beginning (B) and end (A) of the wind blade

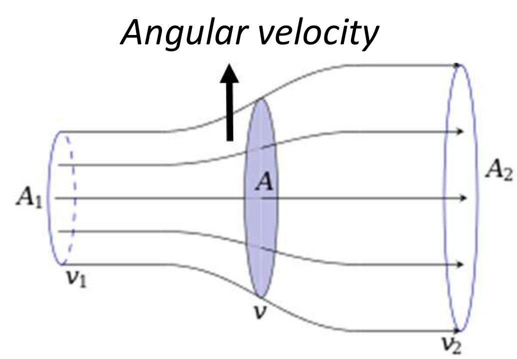
The wind after the turbine has more angular velocity than before

$$P_B + {}^1\!/_2\,\rho\Omega^2 r^2 = P_A + {}^1\!/_2\,\rho(\Omega + \omega)^2 r^2$$

Boring Algebra

$$P_B - P_A = \rho\omega r^2\left(\Omega + {}^1\!/_2\,\omega\right)$$

Ω = angular velocity
ω = incremental increase in angular velocity
r = distance along the blade
R = total blade radius



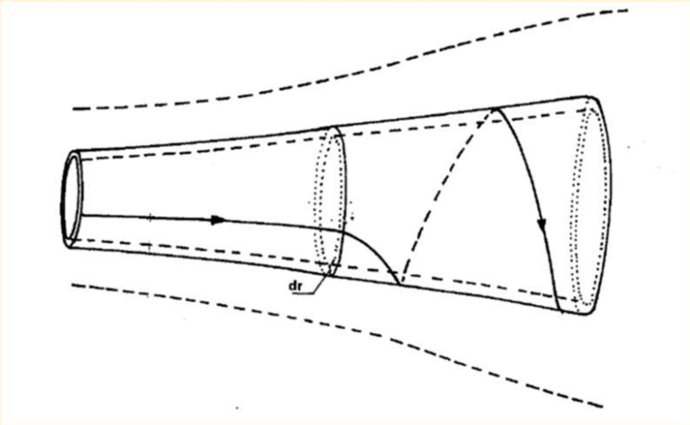
Thrust via Bernoulli's equation

- Thrust on a minute element (dT) gives us:

Force term

Incremental area across circle the turbine blade encompasses

$$dT = \overbrace{(P_B - P_A)dA}^{\text{Force term}} = \rho\omega r^2\left(\Omega + {}^{1}/_{2}\,\omega\right)\overbrace{2\pi r dr}$$



- Lets create an angular induction factor as followed

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

- Applying this to our thrust equation yields:

Boring Algebra

$$dT = 4a'(1 + a')\rho\Omega r^2 \pi r dr$$

Do we want a high a' or a low a' ? Why?

Revisiting Our Linear Thrust

- We want to relate our angular induction (i.e. a') value to V_1. We do this by relating thrusts

- Originally we denoted thrust as: $T = 2S\rho v_1^2 a(1-a)$

- If instead of using the whole surface area (S) we focus on a differential ring for a differential thrust. Thus we get:

$$\mathrm{d}T = 2\rho(2\pi r dr) v_1^2 a(1-a)$$

We calculated thrust from 2 different aspects

- Linear momentum gave us: $dT = 2\rho a(1-a){v_1}^2(2\pi r dr)$
- Bernoulli's equation gave us: $dT = 4a'(1+a')\rho\Omega r^2 \pi r dr$
- Setting the 2 thrusts equal to each other gives us a relationship between angular blade velocity and linear wind velocity:

$$\frac{a(1-a)}{a'(1+a')} = \frac{\Omega^2 r^2}{{v_1}^2} = \lambda_r^2$$

Local speed ratio

- We call λ_r the local speed ratio: $\lambda_r = \frac{\Omega r}{v_1}$
- Whereas λ is the tip speed ratio: $\lambda = \frac{\Omega R}{v_1}$

Remember

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

$$a = 1 - \frac{v_{@T}}{v_1}$$

Torque (F x r)

- To push the turbine blade around we must have a given torque. $d\tau = d(F \times r)$
- The force can be written as followed

$$F = \dot{m} v_{Blade}$$

Linear terms

Angular terms (ν=ω/r)

- If we look at a differential element of torque on our wind blade we have:

$$d\tau = d(\dot{m} v_{Blade} \times r)$$

- By using previous equations we can get this in terms of v_1 and Ω.

- Derivation is in my notes

$$d\tau = v_1(1 - a)\, \rho 2\pi r dr{*}2\Omega a'$$

Power

- We can determine our differential <u>power</u> as a function of torque as followed:

$$dP = d\tau \times \Omega$$

$$dP = 2a'(1-a)\rho v_1 2\pi r \Omega^2 dr$$

- If we want this in terms of our tip speed ratio we will get:

↓ Boring Algebra

$$dP = 4\rho S {v_1}^3 \frac{1}{\lambda^2} a'(1-a)\lambda_r^3 d\lambda_r$$

$$C_P = \int \frac{dP}{P_{Wind}} = \int \frac{dP}{{}^1\!/_2\, S\rho {v_1}^3} = \frac{8}{\lambda^2}\int_0^{\lambda} a'(1-a)\lambda_r^3 d\lambda_r$$

P = Power
d = distance
T = time
v = velocity

Remember

$$\lambda_r = \frac{\Omega r}{v_1}$$

$$\lambda = \frac{\Omega R}{v_1}$$

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

$$a = 1 - \frac{v_{@T}}{v_1}$$

What is ω?

- We have *a′* which is a function of ω, but what is this?
- Rearranging the equation that we first introduced λ_r , we get:

$$a' = -\frac{1}{2} + \frac{1}{2}\sqrt{1 + \frac{4}{\lambda_r^2}a(1-a)}$$

- In terms of ω this is:

$$\omega \;= 2\Omega\left(-\frac{1}{2} + \frac{1}{2}\sqrt{1 + \frac{4}{\lambda_r^2}a(1-a)}\right)$$

If we have a very fast λ_r, what happens to ω?

P = Power
d = distance
T = time
v = velocity

Remember

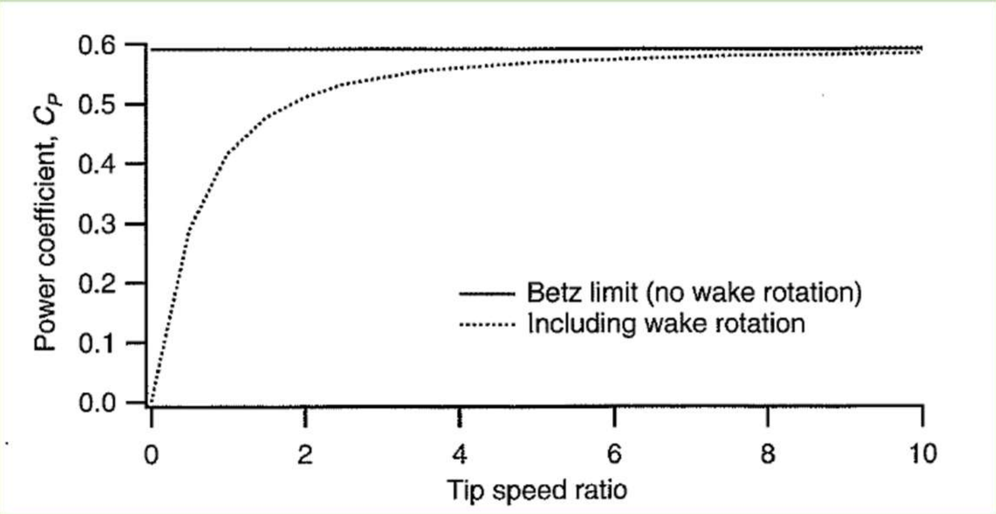
$$\lambda_r = \frac{\Omega r}{v_1}$$

$$\lambda = \frac{\Omega R}{v_1}$$

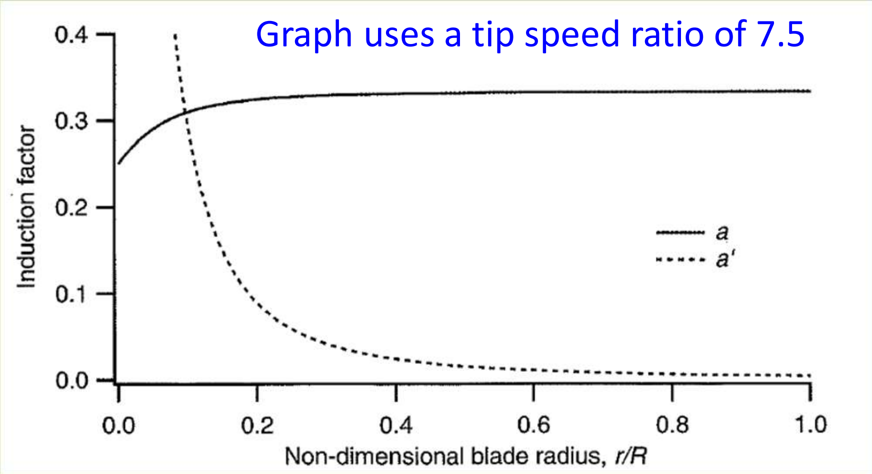
$$a = 1 - \frac{v_{@T}}{v_1}$$

Understanding Wake Rotation

- We know C_p is a function of λ, but what does this mean?
- If your λ is too slow compared to the wind speed you lose efficiency.
- The second graph shows if λ is small, the 'a' value near the middle of the wind turbine is lower than the 1/3 that it should be.

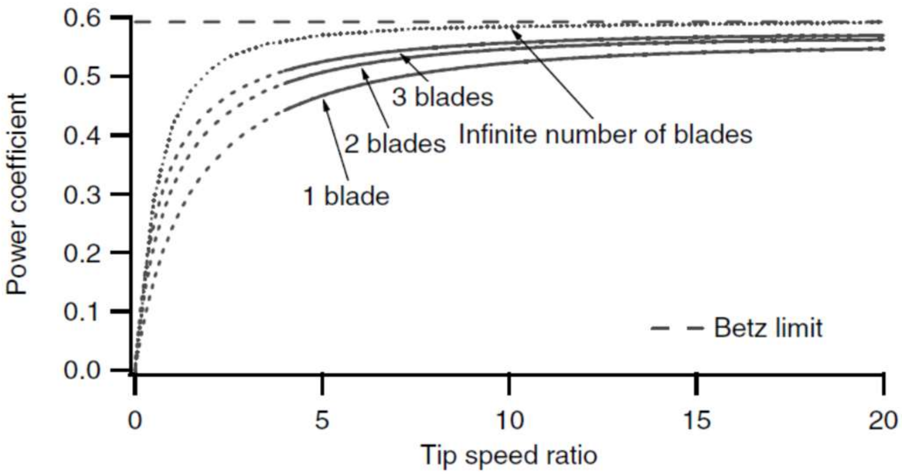


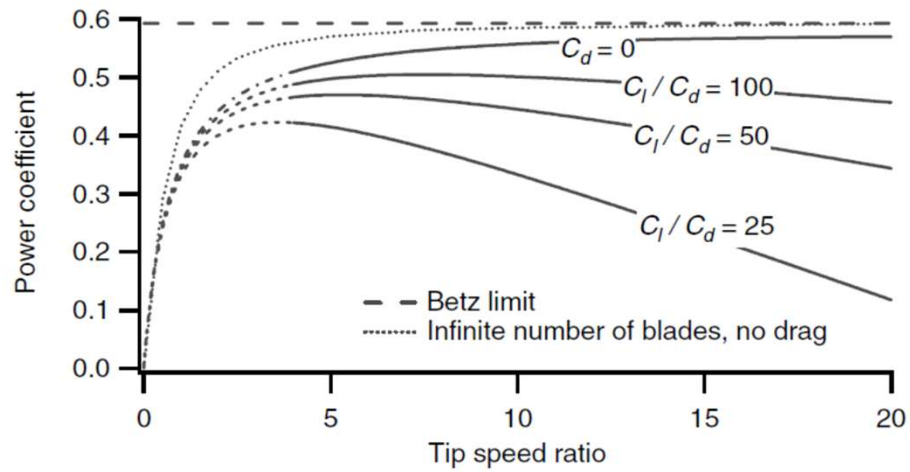
Theoretical case – no drag issues



Optimal number of blades

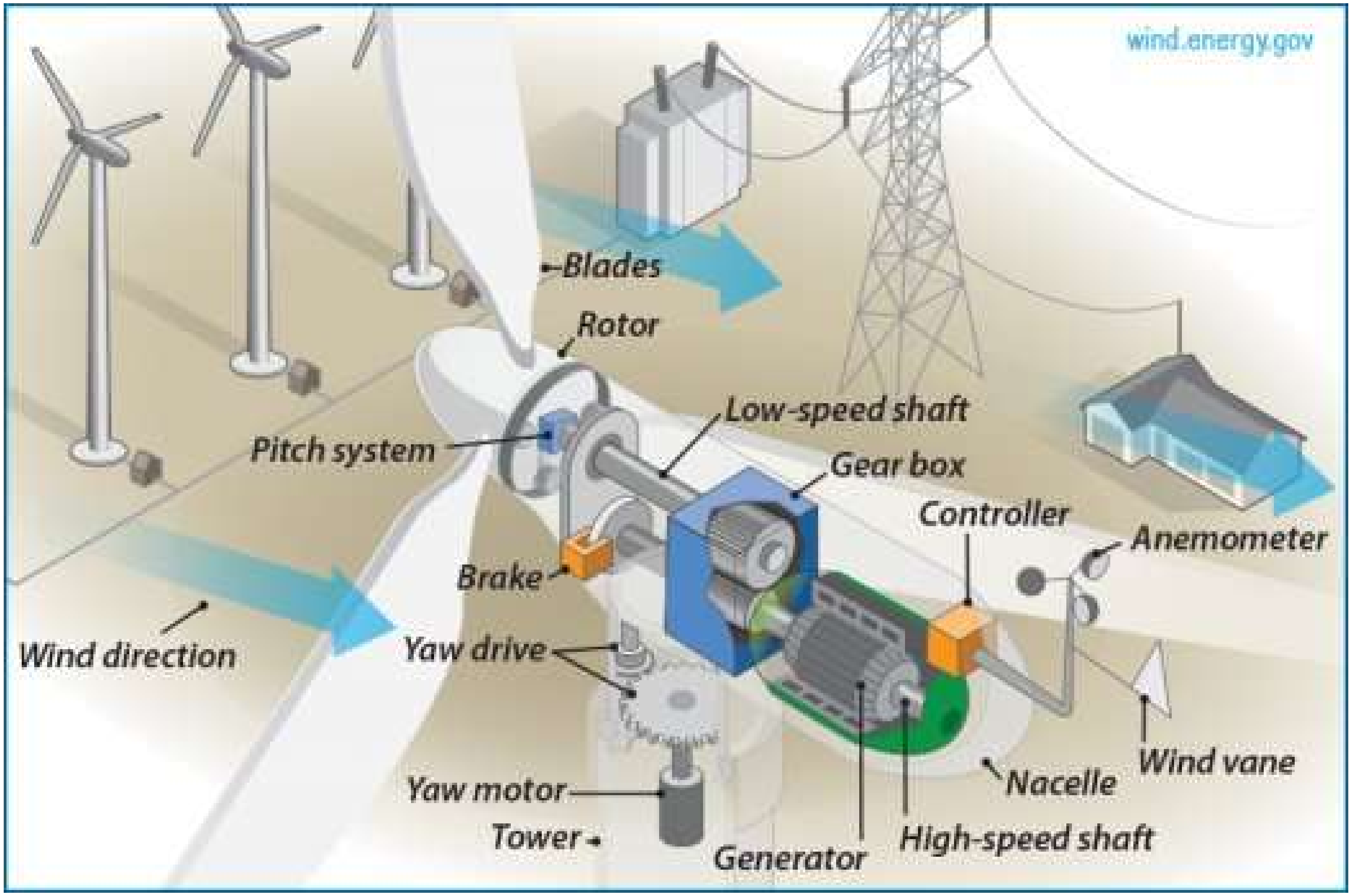
- We need multiple blades to capture all the wind´.
- 3 blades is often used as it gives good mechanical stability.
- If we have drag, efficiency decreases at high tip speeds with bad lift to drag ratios (i.e C_l/C_d)





BREAK

Inside Wind Turbines



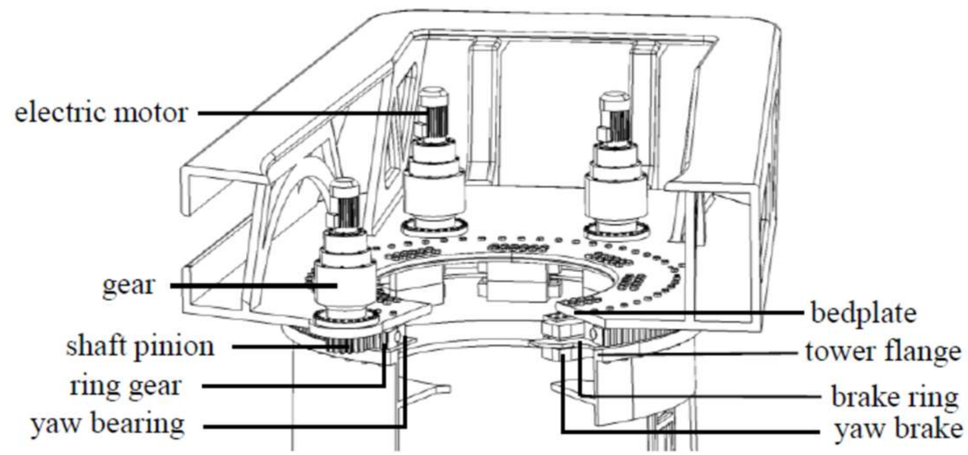
Yaw System

- The Yaw system rotates the blades in the direction of the wind.
- The wind vane is responsible for communicating and controlling rotation.
- Remember Moment of Inertia & Torque

$$I = \frac{M}{V}\int_0^r r^2{}_\perp \, dV \quad \& \quad \tau = I\alpha$$

τ = torque
α = angular acceleration
r = radius perpendicular to axis
V = volume

- Heavy magnets, means high Torque is needed to move/accelerate turbine
- Yaw motor Torque = 200,000 N*m
  Car motor Torque = 250 N*m
- This is 1-5% of total cost.



M-G Kim and Dalhoff, P.H., (2014) J. Phys,: Con. Ser. 524 012086
Doi: 10.1088/1742-6596/524/1/012086

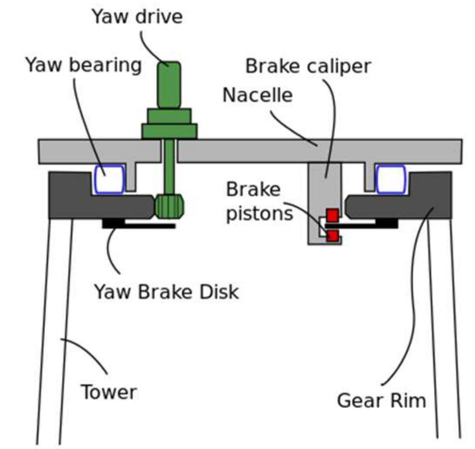
Yaw System

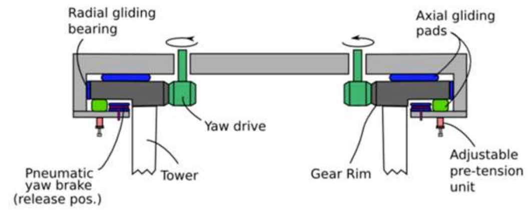
- Typically regular ball bearings are used
  - Double row bearing are used sometimes to decrease wear, but with higher costs

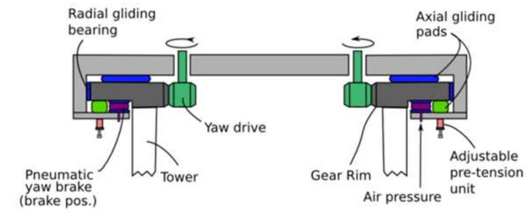
- Sliding bearings
  - Advantages: Sliding can help in braking
  - Disadvantages: Inconsistent sliding, can be loud

- Yaw Braking
  - This is typically done using hydraulics
  - Hydraulics leak, needing maintenance and can even cause fires.

- In general yaw systems and non-technically optimized to reduce on costs.

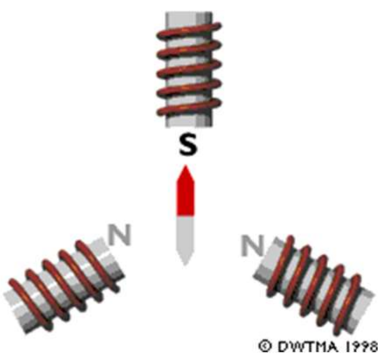




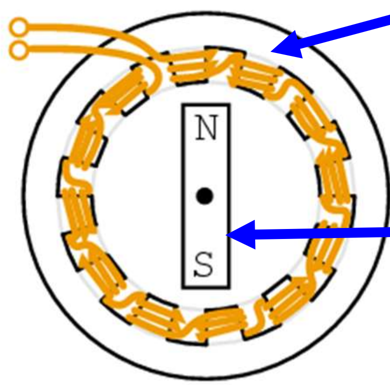


Generators

- Typical 690 V three-phase alternating current (AC-current)
- Thus gearing is essential to produce appropriate current
- A permanent magnet is used with copper windings to generate charge
- Need cooling-normally air, sometimes water



3 phase motor

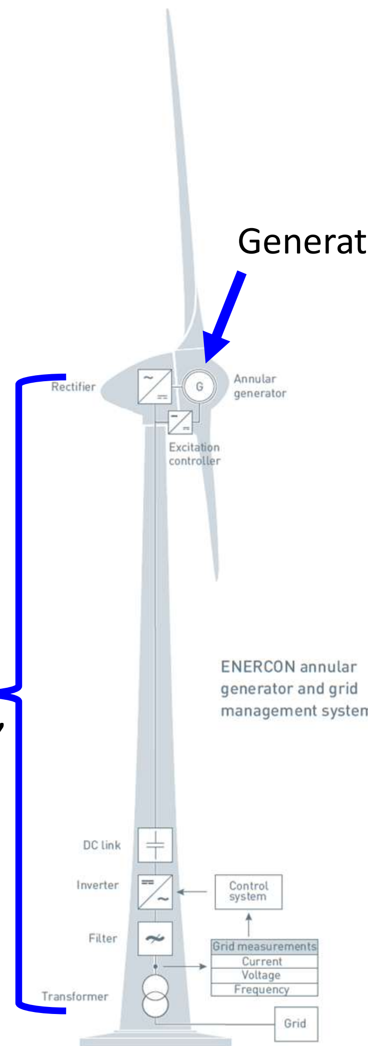


Stator – This is what is static. Normally this is the copper wires

Rotor – This is what rotates. This can be a permanent magnet

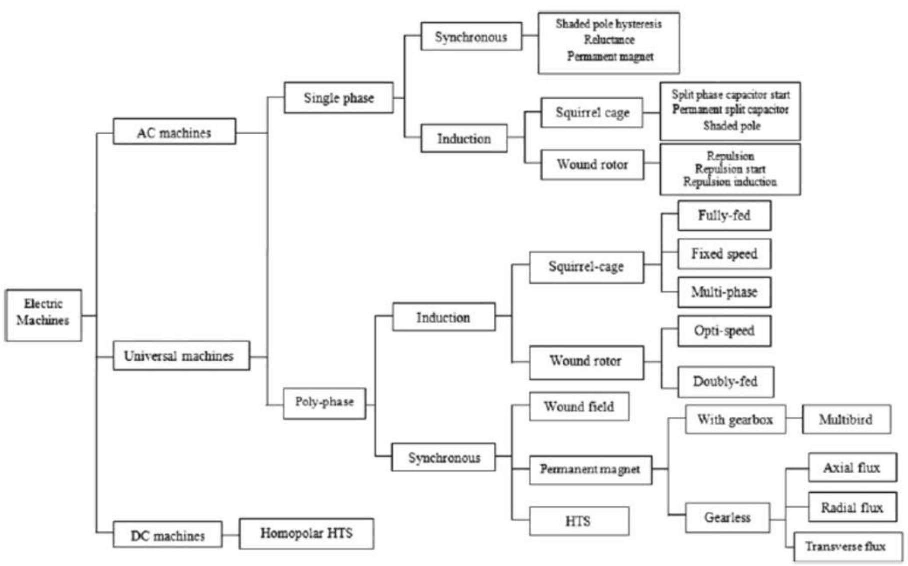
Generator

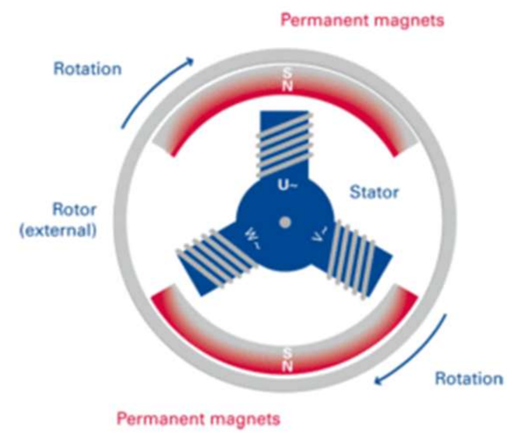
Power 'formatted' for grid



Other Designs

- This field is not completely stable, so new designs are still being investigated
- Some use a shell rotor and a core stator
- Africa sometimes uses smaller wind turbines because roads are too small to handle larger designs.





Vensys systems have the stator and rotor inverted to the standard design

- Economically, it is better to make big wind turbines
- This means really big generators
- Generators can be 30 tons, with 1/3 copper

Gearbox connected generator (Vestas approach)

Pic from RJWeng.com

Direct Drive (no gearbox)- Used by Siemens Gamesa & Enercon)

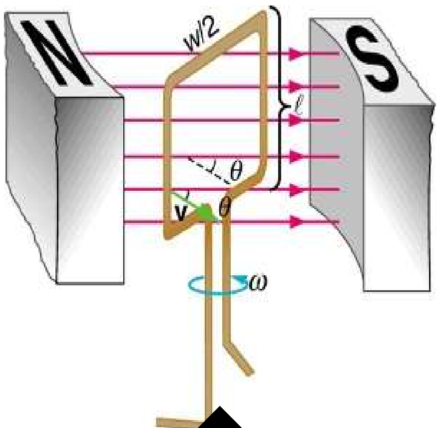
Picture & Data from: Enercon & CopperAlliance.org, respectively

Physics of Generators

Faraday's Law of Induction

$$\Delta V_{ind} = -N\frac{d\Phi_B}{dt}$$

N = # of loops



Wind turbine rotates this

Gaus's Law for Magnetism

$$\Phi_B \equiv \oiint \vec{B} * d\vec{A}$$

$$\Phi_\mathrm{B} = BAcos\theta$$

θ = ωt
(useful since we will rotate)

$$\Phi_\mathrm{B} = BAcos(\omega t)$$

$$\Delta V_{ind} = -NBA\omega sin(\omega t)$$

Physics of Generators

$$\Delta V_{ind} = -NBA\omega sin(\omega t)$$

$$\text{Power} = \Delta V_{ind} * \text{I}$$

- Why can't I just increase the current indefinitely, and get infinite power?

Answer: As the current becomes non-zero, we induce a magnetic torque opposing and movement (i.e. wanting ω=0)

The torque from the wind turbine blade allows us to overcome this magnetic torque.

Physics of Generators

Magnet Side

Magnetic dipole moment

Magnetic field

$$\vec{\tau}_{magnet} = \vec{\mu} \times \vec{B}$$

$$\mu \equiv NiA$$

$$\vec{\tau}_{magn} = NiABsin(\phi t)$$

Blade Side

$$\vec{\tau}_{blade} = rF_{net}$$

$$\mathrm{i} = \frac{rF_{net}}{NBA(\sin\phi t)}$$

Physics of Generators

$$\text{Power} = \Delta V_{ind} * \text{I}$$

$$\Delta V_{ind} = NBA\omega sin(\omega t) * \frac{rF_{net}}{NBA(\sin\phi t)}$$

$$\Delta P_{ind} = rF_{net}\omega sin(\omega' t)$$

Practically there will always be a sinusonal of some frequency

Type of Magnets

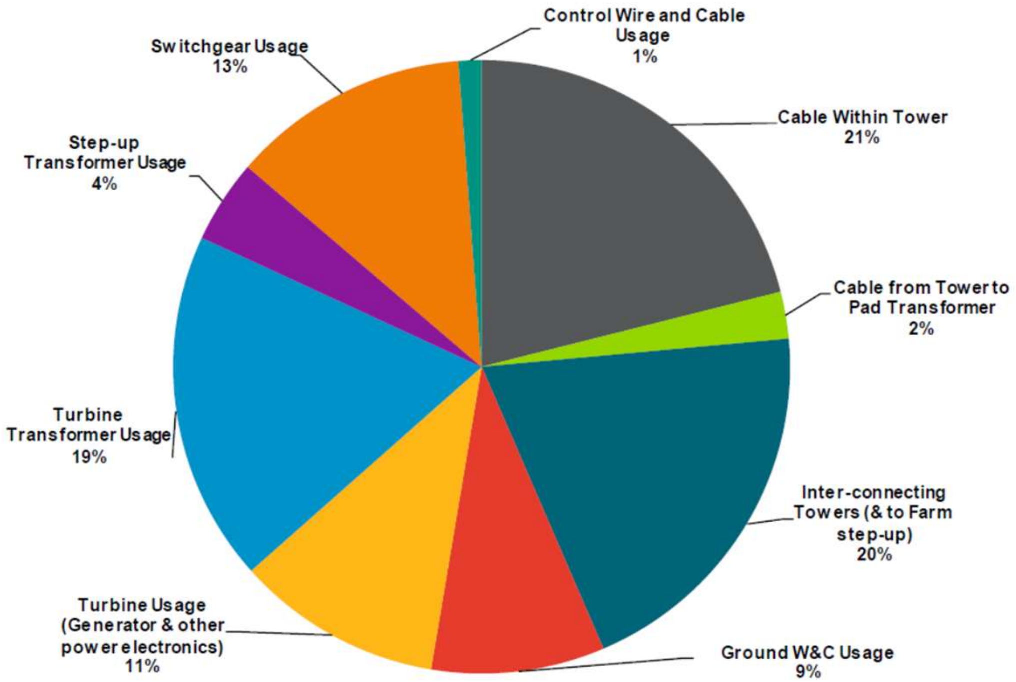
- Originally we had electro-magnets in wind turbine. As of about 2018 this was the most popular approach for wind turbines.

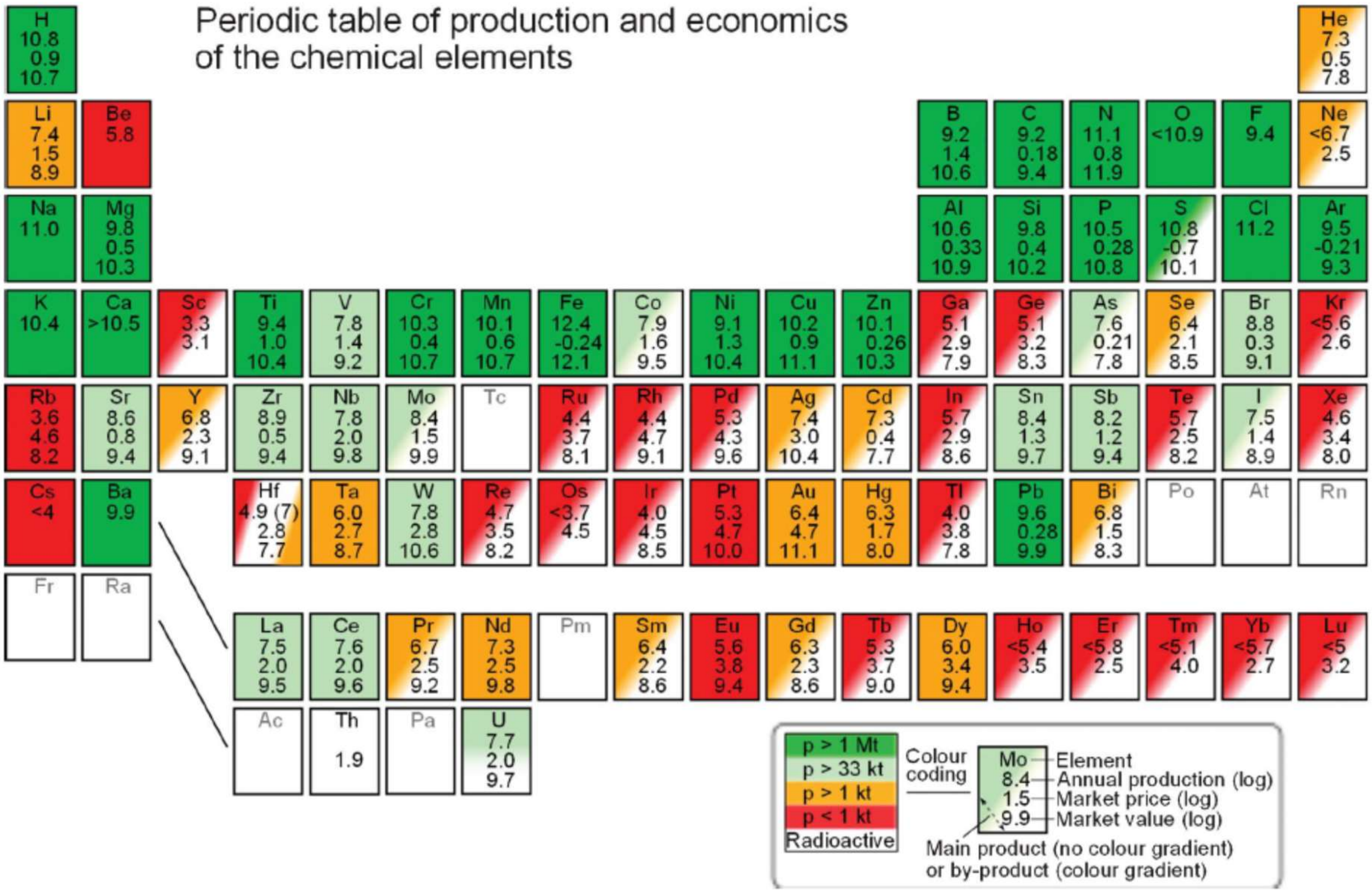
- All new wind turbines have permanent magnets.

- Permanet magents are less complicated, and the benefits outweight their costs.

Copper in Wind Turbines

- Offshore Wind has 10 tons/MW of copper (ref Falconer, 2009)





Vesborg and Jramillo, RSC Advances, 2012,2, 7933–7947, Doi: [10.1039/c2ra20839c](10.1039/c2ra20839c)

Lecture - Learning Objectives

At the end of this lecture you should be able to:

- Understand the thermodynamic limit for wind energy
- Understand how thrust occurs and tip-speed ratio
- Understand the interworkings of a wind turbine
- Understand magnets and how turning of the blade is converted to electrical energy.

For those interested in magnets see the following slides (Not on the exam)

Permanent magents-*Magnetic moments due to spin*

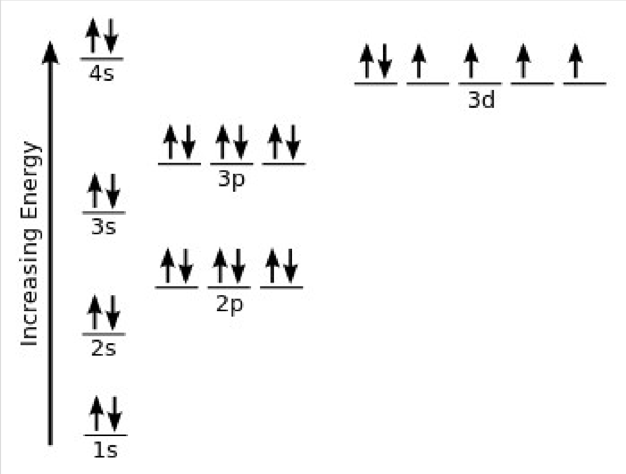
- Electrons spin can provide a dipole moment

$$\vec{\mu}_s = g_{g-fac} \frac{q}{2m} \vec{S}$$

Gg-factor= -2.00 (dimensionless)

- Spin up and spin down will cancel either other out.
- A rough estimate or dipole moment is to look at unparied electrons.
- However the exchange interaction (quantum switching of states) can negate ferromagnetism

Electronic states of Iron



Permanent Magnets

- We need an electric magnetic field to orient magnetic grains

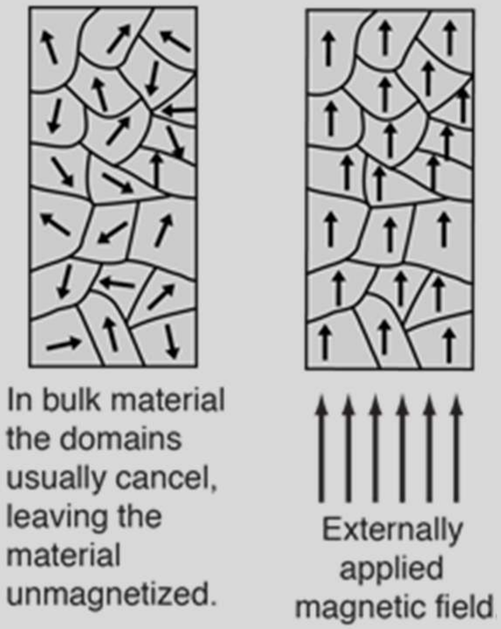


Image from http://hyperphysics.phy-astr.gsu.edu

- Once field is removed, materials stays magnetized
- Once magnetized, how do we distinguish between current induced magnetic field and magnetized field

$$B = \mu_{mag} H$$

Magnet flux density (T)

Magnet field strength (A/m)

Hysteris Charts

- We vary applied magnetization (H) and measure total magnetization (B).

$$B = H + \mu_0 M$$

$$M = \chi_m \frac{H}{\mu_0}$$

Measured via B-H graph and can vary with H

$$\mu_{mag} = (1 + \chi_m)\mu_0$$

$$B = \mu_{mag} H$$

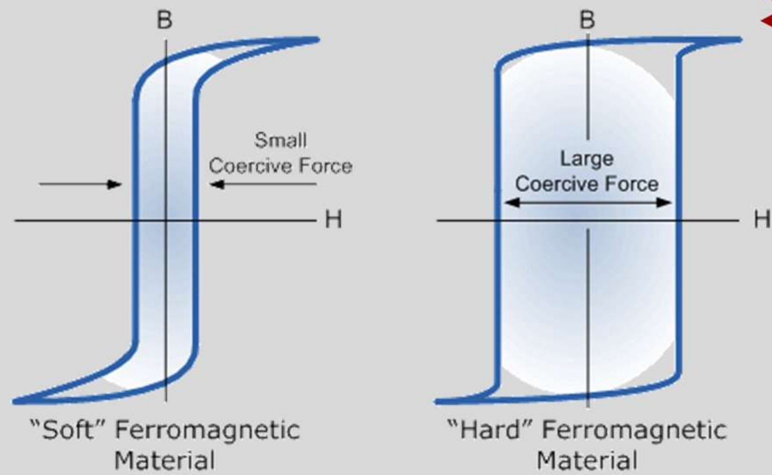


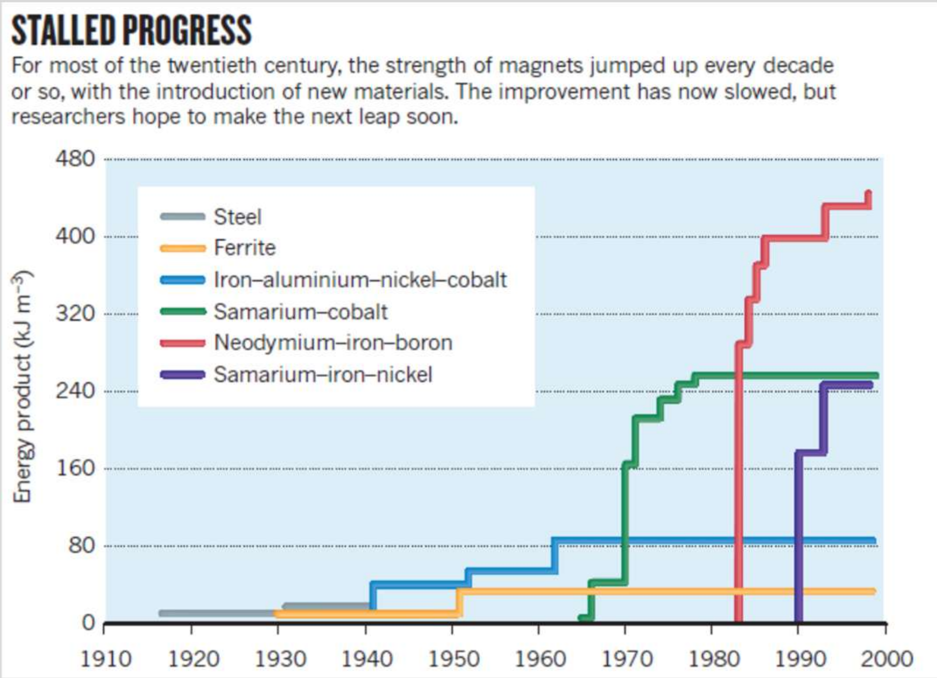
Image from https://www.electronics-tutorials.ws/

- Generators want hard magnets

H = Applied Magnetic Field
B = Total Magnetic Field
(Applied + Magnet)
M = Magnetization
χ_{mag} = Magnetic Susceptibility
μ_{mag} = permeability

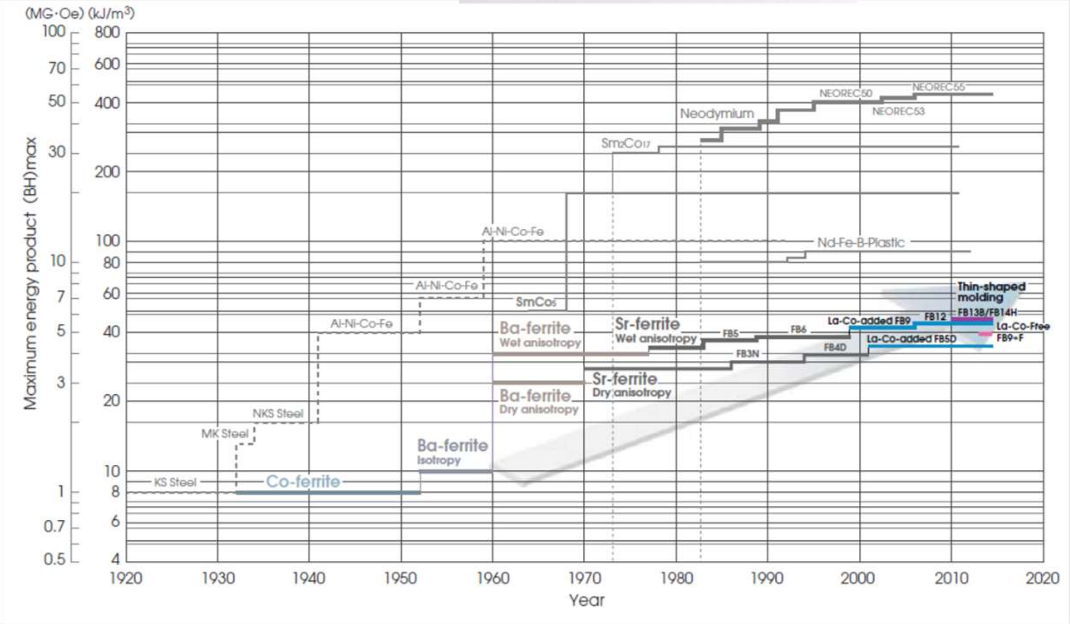
Maximum B-H

- Rather than measure M or μ_{mag}, the product BH is typically used as a figure of merit.
- A higher BH means a better magnet.
- The unit of BH is kJ/m^3, but don't think of it as stored energy.
- Another unit sometimes used is the Mega Gauss-Orsted.
- 1 MGOe = 8 kJ/m^3



Ferrites (Fe_2O_3+ metal)

- Manganese and Nickel alloys give ‘soft’ magnets
- Strontium and Barium alloys give ‘hard magnets
- Since these are iron based, they are really cheap.
- In many situations, they are good enough

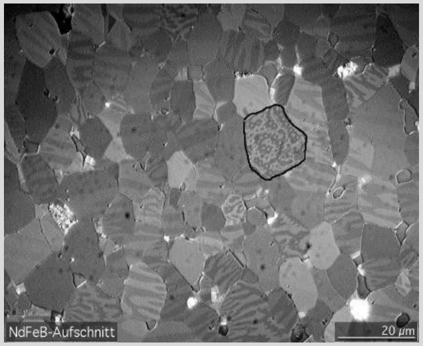


https://product.tdk.com/info/en/catalog/datasheets/magnet_fb_summary_en.pdf

$Nd_2Fe_{14}B$

- Developed in 1982 by General Motors and Susimoto (now Hitachi)
- High magnetocrystalline anisotropy (favors selective crystal growth)
- Nickel plating is usually used to prevent Corrosion.
- Estimate- 50 ktons/yr produced, 80% in China
- BH_{max} =516 KJ/m^3
- Currently 80$/kg

Ni coated $Nd_2Fe_{14}B$



Magnetic grains

Corroded $Nd_2Fe_{14}B$

$SmCo_5$ & Sm_2Co_{17}

- Developed in 1960’s by Karl Strnat and Alden Ray
- High magnetocrystalline anisotropy (favors selective crystal growth)
- These are relatively corrosion resistant
- Advantages- Good at very high tempearture and very low temperature
- Disadvantages- Brittle, need high tempearture to synthesize
- BH_{max} = 112-264 kJ/m^3

$SmCO_5$ magnet

Comparison

- In general Neodynium is the best, unless you need to go to higher temperatures, then Samarium is.

Magnet	B_r (T)	H_{ci} (kA/m)	BH_{max} (kJ/m^3)	T_C (Curie Temperature)	
				(°C)	(°F)
$Nd_2Fe_{14}B$ (sintered)	1.0–1.4	750–2000	200–440	310–400	590–752
$Nd_2Fe_{14}B$ (bonded)	0.6–0.7	600–1200	60–100	310–400	590–752
$SmCo_5$ (sintered)	0.8–1.1	600–2000	120–200	720	1328
$Sm(Co, Fe, Cu, Zr)_7$ (sintered)	0.9–1.15	450–1300	150–240	800	1472
Alnico (sintered)	0.6–1.4	275	10–88	700–860	1292–1580
Sr-ferrite (sintered)	0.2–0.78	100–300	10–40	450	842

Materials

- Basically we are looking to produce 17-30 TW of energy from nothing.
- If a rare material is cheap now, will it still be cheap if we need 30 TW of it?
- How much do we produce of a given material and is it enough?
- Lets look at wind turbines- what are the major components?