Wind Energy Fundamentals

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

• Understand the thermodynamic limit for wind energy
• Understand how thrust occurs and how it turns the blade
• Understand the interworkings of a wind turbine
• Understand magnets and how turning of the blade is converted to electrical energy.
Power

• How much power does wind provide.

• Lets break this down as followed:

\[ E = \frac{1}{2} m v^2 \quad \text{Eqn for kinetic energy} \]

\[ P = \frac{\Delta E}{\Delta t} = \frac{\Delta \frac{1}{2} m v^2}{\Delta t} = \frac{1}{2} m v^2 = \frac{1}{2} (A \rho v) v^2 \]

\[ \text{Mass flow rate} \]

\[ P_{\text{wind}} = \frac{1}{2} A \rho v^3 \]

• Power scales with velocity to the 3rd power. (Practical losses often scale with velocity to the 1st power, thus often actual power scales with velocity to the 2nd 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 \((A_2, V_2)\) will have a smaller, yet significant wind velocity than the incoming wind \((A_1, V_1)\).

Wind coming in \(A_1\) \(V_1\) \(A\) Wind turbine \(V\) Wind leaving \(A_2\)
Wind Power from Turbines

- From kinetic energy we know:
  \[ E = \frac{1}{2} m v^2 \]
  Different wind velocity before and after wind turbine
  \[ \Delta E = \frac{1}{2} m (v_1^2 - v_2^2) \]
  Mass flow rate
  \[ P = \frac{\Delta E}{\Delta t} = \frac{1}{2} \frac{m}{\Delta t} (v_1^2 - v_2^2) \]

- 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:

\[ F = ma = m \frac{dv}{dt} = m \frac{\Delta v}{\Delta t} = \dot{m} \Delta v = \rho S v @ A (v_1 - v_2) \]

Mass flow rate

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

\[ P = \frac{dE}{dt} = \frac{d(F \times x)}{dt} = F \frac{dx}{dt} = \rho S v @ A (v_1 - v_2) * v @ A = \rho S v_{@ A}^2 (v_1 - v_2) \]

• 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: \[ P = \frac{1}{2} \rho S v_A(v_1^2 - v_2^2) \]

• From force balance we know our turbine power is: \[ P = \rho S v_A^2 (v_1 - v_2) \]

• What this tells us is that \( v_1, v_2 \) and \( v_A \) 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 \( v_A \) we get:

\[
\frac{1}{2} \rho S v_A(v_1^2 - v_2^2) = \rho S v_A^2 (v_1 - v_2)
\]

Boring algebra

\[ v_A = \frac{1}{2} (v_2 + v_1) \]
Maximum Wind Power

• From kinetic energy we know:  
\[ P = \frac{1}{2} \rho S v_{@A} (v_1^2 - v_2^2) \]

or
\[ P = \frac{1}{4} \rho S (v_2 + v_1)(v_1^2 - v_2^2) \]

• Now we know what \( v_{@A} \) is, however we have to figure out what our maximum power can be.

• The way to find maximum power is to take the derivative and set it to 0.

• But what should we take the derivative of? The variable in this system that we can control is \( v_2 \), so you may think take the derivative with respect to \( v_2 \).

• 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:
\[ P = \frac{1}{4} \rho S v_1^3 \left( -\left( \frac{v_2}{v_1} \right)^3 - \left( \frac{v_2}{v_1} \right)^2 + \frac{v_2}{v_1} + 1 \right) \]
Maximum Wind Power

• We need to take the derivative of:

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

and set it equal to zero

• Thus

$$\frac{dP}{d \left( \frac{v_2}{v_1} \right)} = 0 \quad \Rightarrow \quad \frac{v_2}{v_1} = 1/3$$

• And thus the power from our wind turbine is:

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

\(\%\) Efficient
Another way to look at things

• If the maximum wind turbine power is: \( P_{\text{Turbine}} = \frac{16}{27} \times \frac{1}{2} \rho S v_1^3 \)
• And the total power from the incoming wind is: \( P_{\text{Wind}} = \frac{1}{2} m v_1^2 \) (m=Mass flow rate)

\[ P_{\text{Wind}} = \frac{1}{2} \rho S v_1^3 \]

• Thus: \( \frac{P_{\text{Turbine}}}{P_{\text{Wind}}} = \frac{\frac{16}{27} \times \frac{1}{2} \rho S v_1^3}{\frac{1}{2} \rho S v_1^3} = \frac{16}{27} = 59\% \)

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

• A major key to achieving this is to make sure you have the proper \( v_2/v_1 \) ratio
Maximum Wind Power

Instead of this diagram, we can use this diagram

These ratios are true because of what we derived earlier:

\[ v_{@A} = \frac{1}{2} (v_2 + v_1) \]

Axial interference cofactor \[ a = 1 - \frac{v}{V_0} \]

\[ a_{max} = \frac{1}{3} \]

\( v \) = velocity at wind turbine
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

$$= \frac{\rho S v_A^2 (v_2 - v_1)}{\frac{1}{2} \rho S V_1^3}$$

Terminology from Figure B of previous slide

$$= \frac{\rho S v^2 (V_0 (1 - 2a) - V_0)}{\frac{1}{2} \rho S V_0^3}$$

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 $C_p$. 
Thrust

• Given our velocity slows down across the wind turbine we lose some momentum.

• Conservation of momentum says this must go somewhere.

• This momentum goes into the thrust of our wind blades, which then provides the basis for energy in our turbines

• Thrust (T) is then:

\[
T = \frac{dm}{dt} v_{\text{Blade}} = \rho S v V_0 2a = 2\rho S v V_0 \left(1 - \frac{v}{V_0}\right) = 2\rho S v (V_0 - v)
\]

• Power can also be related in terms of thrust:

\[
P = \frac{E}{t} = \frac{F \times d}{t} = \frac{F \times d}{t} = Fv = T v = 2\rho S v^2 (V_0 - v)
\]
Thrust

• Since we have a $C_p$, we can also have a thrust coefficient ($C_T$) as followed:

$$C_T = \frac{\text{Thrust Force}}{\text{Maximum Force from wind}} = \frac{2\rho Sv(V_0 - v)}{1/2 \rho A v^2}$$

• If $C_T$ is near 1 that means there is incredible force on our wind turbine, but the velocity of the air is very small. (In terms of solar cells: think lots of voltage very little current)

• If $C_T$ is near 0 that means there is little force on our wind turbine, but the velocity of the air is large. (In terms of solar cells: think lots of current very little voltage)
Optimal Thrust Coefficient

• The optimal $C_T$ is $8/9$.

• The table below plots $C_p$ and $C_T$ as a function of $\alpha$
Wind Energy

How does a wind turbine work?

- The wind hits the rotor plane
- The combination of wind speed and blade rotation results in a pressure distribution on the rotor blades
- The pressure distribution causes a turning moment (torque)
- The turning moment rotates the shaft
- The shaft is coupled to a generator that produces electrical power
How do we actually move 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’.

- Varying the angle changes the Lift and Drag ratio.

- This is a function of wind blade design

- Beyond a certain angle the turbulence reaches the lift point, and drastically decreases lift.
  - This is called ‘Stall’

- The exact aerodynamics is beyond the scope of this class.
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

\[ P_B + \frac{1}{2} \rho \Omega^2 r^2 = P_A + \frac{1}{2} \rho (\Omega + \omega)^2 r^2 \]

\[ P_B - P_A = \rho \omega r^2 (\Omega + \frac{1}{2} \omega) \]

The wind after the turbine has more angular velocity than before

\( \Omega \) = angular velocity
\( \omega \) = incremental increase in angular velocity
\( r \) = distance along the blade
\( R \) = total blade radius

Boring Algebra
Thrust via Bernoulli’s equation

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

\[ dT = (P_B - P_A)dA = \rho \omega r^2 (\Omega + \frac{1}{2} \omega) 2\pi r dr \]

- Let's create an angular induction factor as followed:

\[ a' = \frac{\omega}{2\Omega} \]

- Applying this to our thrust equation yields:

\[ dT = 4a'(1 + a')\rho \Omega r^2 \pi r dr \]
Revisiting Our Linear Thrust

• Originally we denoted thrust as:

\[ T = 2\rho S v (V_0 - v) \]

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

\[ dT = 2\rho (2\pi r dr) v (V_0 - v) \]

• Now we want to get this in terms of \( a \) as followed:

\[ T = 2\rho (2\pi r dr) v (V_0 - v) \]

Remember
\[ a = 1 - \frac{v}{V_0} \]

Boring Algebra

\[ T = 2\rho a (1 - a) V_0^2 (2\pi r dr) \]
We Calculated Thrust 2 Different ways

- Linear momentum gave us: \( dT = 2\rho a(1 - a)V_0^2 (2\pi r dr) \)
- 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 turbine velocity and linear wind velocity:

\[
\frac{a(1 - a)}{a'(1 + a')} = \frac{\Omega^2 r^2}{V_0^2} = \lambda_r^2
\]

We call \( \lambda_r \) the local speed ratio: \( \lambda_r = \frac{\Omega r}{V_0} \)
- Whereas \( \lambda \) is the tip speed ratio: \( \lambda = \frac{\Omega R}{V_0} \)

\[
\text{Remember}
\]
\[
a' = \frac{\omega}{2\Omega}
\]
\[
a = 1 - \frac{v}{V_0}
\]
Torque

• To push the turbine blade around we must have a given torque.

• This torque comes from change in angular momentum of wake (conservation of angular momentum).

• If we look at a differential element of Torque on our wind blade we have:

\[ dQ = d(\dot{m}(\omega r) \times r) \]

• We can get this in terms of our incoming velocity since from Slide 11:

\[ v = V_0(1 - a) \]

• We can get eliminate ‘\( \omega \)’ by noting that from Slide 19:

\[ a' = \frac{\omega}{2\Omega} \]

\[ dQ = V_0(1 - a)2\Omega a' \rho 2\pi r dr \]
Torque

• We can determine our differential power as a function of torque as followed:

\[ dP = d \left( \frac{F \times d}{t} \right) = dQ \times \Omega \]

\[ dP = 2a'(1 - a)\rho v^2\pi r^2 \Omega dr \]

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

\[ \Lambda_r = \frac{\Omega r}{V_0} \]

\[ \Lambda = \frac{\Omega R}{V_0} \]

\[ a' = \frac{\omega}{2\Omega} \]

\[ a = 1 - \frac{v}{V_0} \]
What is $\omega$?

- We have $a'$ which is a function of $\omega$, but what is this?

- Without derivation we can relate $a'$ to $a$ and $\lambda_r$ as followed:

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

- In terms of $\omega$ this is:

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

Remember:

- $P = \text{Power}$
- $\lambda = \frac{\Omega R}{V_0}$
- $\lambda_r = \frac{\Omega r}{V_0}$
- $a' = \frac{\omega}{2\Omega}$
- $a = 1 - \frac{v}{V_0}$
Understanding Wake Rotation

- We know $C_p$ is a function of $\lambda$, but what does this mean?

- If your $\lambda$ is too slow compared to the wind speed you lose efficiency.

- The second graph shows if $\lambda$ is small, the ‘a’ value near the middle of the wind turbine is lower than the 1/3 that it should be.

![Graph](image)

Graph uses a tip speed ratio of 7.5
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 Inertia & Torque

\[ I = \frac{M}{V} \int_{0}^{r} r^2 dV \quad \text{&} \quad \tau = I \alpha \]

• 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.

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
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

Direct Drive (no gearbox)

Gearbox connected generator

Picture & Data from: Enercon & CopperAlliance.org, respectively
Physics of Generators

Faraday’s Law of Induction

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

Gauss’s Law for Magnetism

$$\Phi_B = \int \int \vec{B} \cdot \vec{dA}$$

$$\Phi_B = BA\cos\theta$$

$$\Delta P_{ind} = rF\omega \sin(\omega t)$$
Magnetic moments due to spin

• Electrons spin can provide a dipole moment

\[ \hat{\mu}_s = g_{g\text{-factor}} \frac{q}{2m} \hat{S} \]

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 unpaired electrons.

• However the exchange interaction (quantum switching of states) can negate ferromagnetism

Electronic states of Iron

- 1s
- 2s
- 3s
- 3p
- 4s
- 3d

Increasing Energy
Permanent Magnets

- We need an electric magnetic field to orient magnetic grains
- 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 field strength (A/m)  Magnet flux density (T)

Image from [http://hyperphysics.phy-astr.gsu.edu](http://hyperphysics.phy-astr.gsu.edu)
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*

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

\[ B = \mu_{mag} H \]

- Generators want hard magnets

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

\( H = \) Applied Magnetic Field
\( B = \) Total Magnetic Field  
\( \) (Applied + Magnet)
\( M = \) Magnetization
\( \chi_{mag} = \) Magnetic Susceptibility
\( \mu_{mag} = \) permeability
Maximum B-H

- Rather than measure $M$ or $\mu_{\text{mag}}$, 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.
- $1\ \text{MGOe} = 8\ \text{kJ/m}^3$
Ferrites (Fe$_2$O$_3$+ 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

Nd$_2$Fe$_{14}$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.

- **50 ktons/yr produced, 95% in China**

- $\text{BH}_{\text{max}} = 516 \text{ KJ/m}^3$
SmCo$_5$ & Sm$_2$Co$_{17}$

- 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 temperature and very low temperature

- Disadvantages- Brittle, need high temperature to synthesize

- $BH_{\text{max}} = 112-264$ kJ/m$^3$
Comparison

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

<table>
<thead>
<tr>
<th>Magnet</th>
<th>$B_r$ (T)</th>
<th>$H_{ci}$ (kA/m)</th>
<th>$BH_{max}$ (kJ/m$^3$)</th>
<th>$T_C$ (Curie Temperature)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(°C)</td>
</tr>
<tr>
<td>$\text{Nd}<em>2\text{Fe}</em>{14}\text{B (sintered)}$</td>
<td>1.0–1.4</td>
<td>750–2000</td>
<td>200–440</td>
<td>310–400</td>
</tr>
<tr>
<td>$\text{Nd}<em>2\text{Fe}</em>{14}\text{B (bonded)}$</td>
<td>0.6–0.7</td>
<td>600–1200</td>
<td>60–100</td>
<td>310–400</td>
</tr>
<tr>
<td>$\text{SmCo}_5$ (sintered)</td>
<td>0.8–1.1</td>
<td>600–2000</td>
<td>120–200</td>
<td>720</td>
</tr>
<tr>
<td>$\text{Sm(Co, Fe, Cu, Zr)}_7$ (sintered)</td>
<td>0.9–1.15</td>
<td>450–1300</td>
<td>150–240</td>
<td>800</td>
</tr>
<tr>
<td>$\text{Alnico (sintered)}$</td>
<td>0.6–1.4</td>
<td>275</td>
<td>10–88</td>
<td>700–860</td>
</tr>
<tr>
<td>$\text{Sr-ferrite (sintered)}$</td>
<td>0.2–0.78</td>
<td>100–300</td>
<td>10–40</td>
<td>450</td>
</tr>
</tbody>
</table>
Magnetism at DTU Physics

• Magnetism and magnetic materials
  • Taught by: Catherine Frandsen
  • Spring F5B

• Catherine also researches nanoparticle magnets

• The basic strategy is get a high ‘B’ material and a high ‘H’ material, and mix them to get a high BH material

**MIX and MATCH**

Nanocomposite magnets, like many other composite materials, combine two substances with complementary properties

1. MAKE PARTICLES
   One set must be magnetically “hard” (red); the other set (gray) must be strongly magnetized.

2. COMBINE THEM
   Align the hard particles and mix them with the strongly magnetized ones
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?

• Basically how much do we produce of a given material and is it enough?

• Lets look at wind turbines- what are the major components?
Copper in Wind Turbines

- Offshore Wind has 10 tons/MW of copper (ref Falconer, 2009)
Periodic table of production and economics of the chemical elements

<table>
<thead>
<tr>
<th>Element</th>
<th>Production (log)</th>
<th>Market price (log)</th>
<th>Market value (log)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>1.4</td>
<td>0.18</td>
<td>0.9</td>
</tr>
<tr>
<td>Li</td>
<td>10.6</td>
<td>0.9</td>
<td>1.5</td>
</tr>
<tr>
<td>Be</td>
<td>8.9</td>
<td>0.5</td>
<td>7.8</td>
</tr>
<tr>
<td>Na</td>
<td>11.0</td>
<td>9.4</td>
<td>10.9</td>
</tr>
<tr>
<td>Mg</td>
<td>9.8</td>
<td>0.4</td>
<td>10.2</td>
</tr>
<tr>
<td>Al</td>
<td>10.6</td>
<td>0.33</td>
<td>10.9</td>
</tr>
<tr>
<td>Si</td>
<td>9.8</td>
<td>0.4</td>
<td>10.2</td>
</tr>
<tr>
<td>P</td>
<td>10.5</td>
<td>0.28</td>
<td>10.8</td>
</tr>
<tr>
<td>S</td>
<td>9.5</td>
<td>0.02</td>
<td>9.9</td>
</tr>
<tr>
<td>Cl</td>
<td>11.2</td>
<td>0.21</td>
<td>10.1</td>
</tr>
<tr>
<td>Ar</td>
<td>9.5</td>
<td>0.21</td>
<td>9.3</td>
</tr>
<tr>
<td>K</td>
<td>10.4</td>
<td>1.0</td>
<td>9.2</td>
</tr>
<tr>
<td>Ca</td>
<td>&gt;10.5</td>
<td>1.5</td>
<td>9.6</td>
</tr>
<tr>
<td>Sc</td>
<td>3.3</td>
<td>3.1</td>
<td>3.6</td>
</tr>
<tr>
<td>Ti</td>
<td>9.4</td>
<td>1.0</td>
<td>2.3</td>
</tr>
<tr>
<td>V</td>
<td>7.8</td>
<td>1.0</td>
<td>2.3</td>
</tr>
<tr>
<td>Cr</td>
<td>10.3</td>
<td>1.0</td>
<td>2.3</td>
</tr>
<tr>
<td>Mn</td>
<td>10.1</td>
<td>1.0</td>
<td>2.3</td>
</tr>
<tr>
<td>Fe</td>
<td>12.4</td>
<td>0.24</td>
<td>2.3</td>
</tr>
<tr>
<td>Co</td>
<td>7.9</td>
<td>1.6</td>
<td>2.3</td>
</tr>
<tr>
<td>Ni</td>
<td>9.1</td>
<td>1.3</td>
<td>2.3</td>
</tr>
<tr>
<td>Cu</td>
<td>10.2</td>
<td>0.9</td>
<td>2.3</td>
</tr>
<tr>
<td>Zn</td>
<td>10.1</td>
<td>1.22</td>
<td>2.3</td>
</tr>
<tr>
<td>Ga</td>
<td>5.1</td>
<td>0.32</td>
<td>2.3</td>
</tr>
<tr>
<td>Ge</td>
<td>8.6</td>
<td>0.21</td>
<td>2.3</td>
</tr>
<tr>
<td>As</td>
<td>8.8</td>
<td>0.21</td>
<td>2.3</td>
</tr>
<tr>
<td>Se</td>
<td>8.8</td>
<td>0.21</td>
<td>2.3</td>
</tr>
<tr>
<td>Br</td>
<td>8.8</td>
<td>0.21</td>
<td>2.3</td>
</tr>
<tr>
<td>Kr</td>
<td>8.8</td>
<td>0.21</td>
<td>2.3</td>
</tr>
<tr>
<td>Rb</td>
<td>3.6</td>
<td>0.8</td>
<td>2.3</td>
</tr>
<tr>
<td>Sr</td>
<td>4.6</td>
<td>0.8</td>
<td>2.3</td>
</tr>
<tr>
<td>Y</td>
<td>8.2</td>
<td>0.8</td>
<td>2.3</td>
</tr>
<tr>
<td>Zr</td>
<td>8.9</td>
<td>0.8</td>
<td>2.3</td>
</tr>
<tr>
<td>Nb</td>
<td>7.8</td>
<td>0.8</td>
<td>2.3</td>
</tr>
<tr>
<td>Mo</td>
<td>8.4</td>
<td>0.8</td>
<td>2.3</td>
</tr>
<tr>
<td>Tc</td>
<td>7.7</td>
<td>0.8</td>
<td>2.3</td>
</tr>
<tr>
<td>Ru</td>
<td>7.7</td>
<td>0.8</td>
<td>2.3</td>
</tr>
<tr>
<td>Rh</td>
<td>7.7</td>
<td>0.8</td>
<td>2.3</td>
</tr>
<tr>
<td>Pd</td>
<td>7.7</td>
<td>0.8</td>
<td>2.3</td>
</tr>
<tr>
<td>Ag</td>
<td>7.7</td>
<td>0.8</td>
<td>2.3</td>
</tr>
<tr>
<td>Cd</td>
<td>7.7</td>
<td>0.8</td>
<td>2.3</td>
</tr>
<tr>
<td>In</td>
<td>7.7</td>
<td>0.8</td>
<td>2.3</td>
</tr>
<tr>
<td>Sn</td>
<td>7.7</td>
<td>0.8</td>
<td>2.3</td>
</tr>
<tr>
<td>Sb</td>
<td>7.7</td>
<td>0.8</td>
<td>2.3</td>
</tr>
<tr>
<td>Te</td>
<td>7.7</td>
<td>0.8</td>
<td>2.3</td>
</tr>
<tr>
<td>I</td>
<td>7.7</td>
<td>0.8</td>
<td>2.3</td>
</tr>
<tr>
<td>Xe</td>
<td>7.7</td>
<td>0.8</td>
<td>2.3</td>
</tr>
<tr>
<td>Cs</td>
<td>&lt;4</td>
<td>0.8</td>
<td>2.3</td>
</tr>
<tr>
<td>Ba</td>
<td>9.9</td>
<td>0.8</td>
<td>2.3</td>
</tr>
<tr>
<td>Fr</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Ra</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Ra</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Electro-Magnets

- By inducing a magnetic field via current, you reduce the need for permanent magnets.

- Basically you just have 2 copper wires with different electrical currents/magnetic fields between them.

- 77% of wind turbine use electromagnets, but this will drop to 60% in next 10 years.

- Matching phases can be more complicated, but that is all done electronically.

- This is a little heavier and more expensive though.