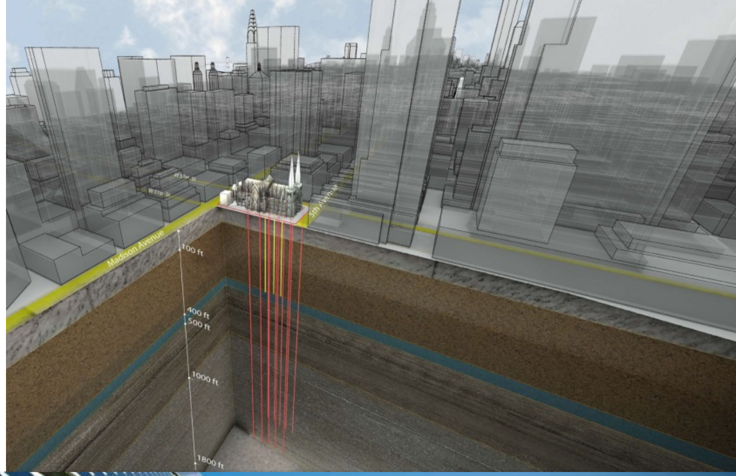
Radioactivity

Lecture 19

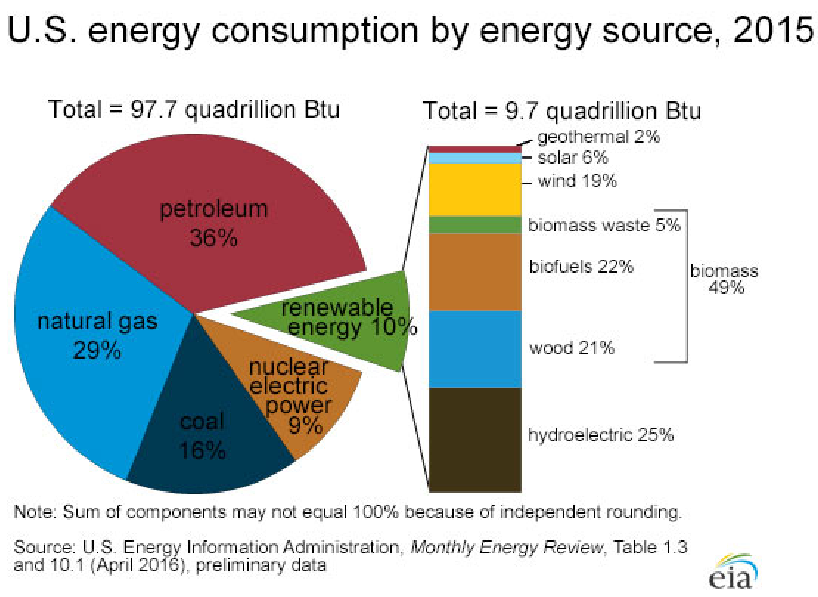
Radioactivity and Renewable Energies

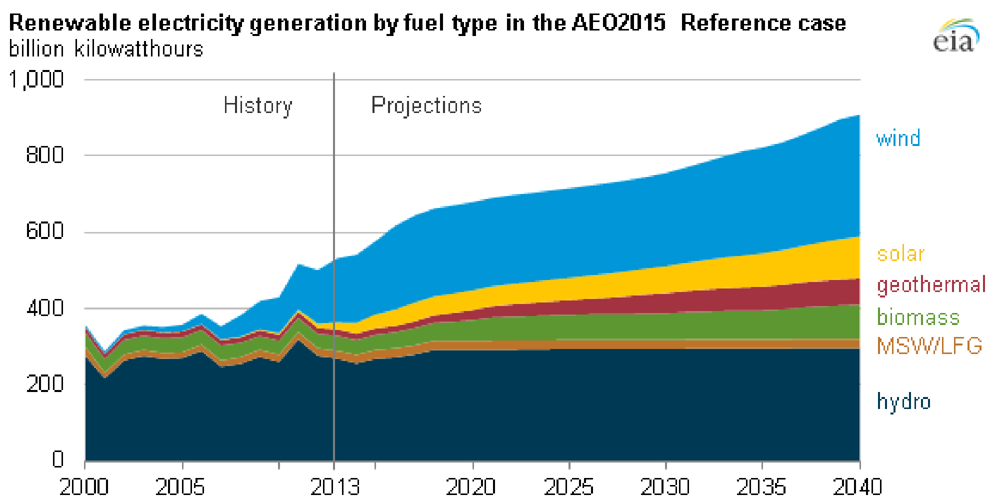
Renewable Energies



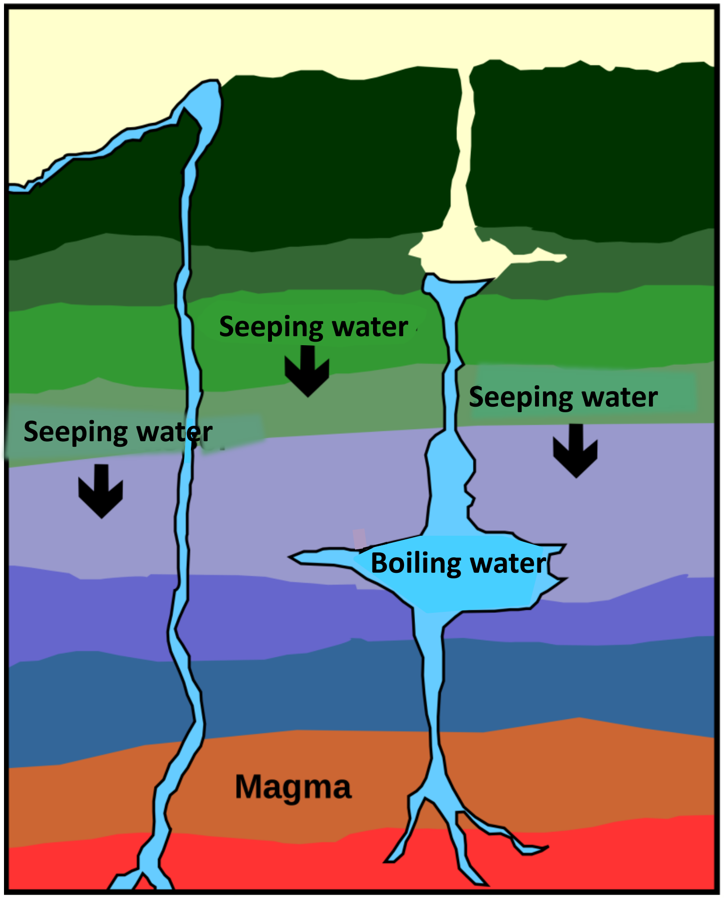
- Fossil fuel is bad
- Nuclear fuel is bad
- Renewable energy is the solution!?

Energy Needs and Projections



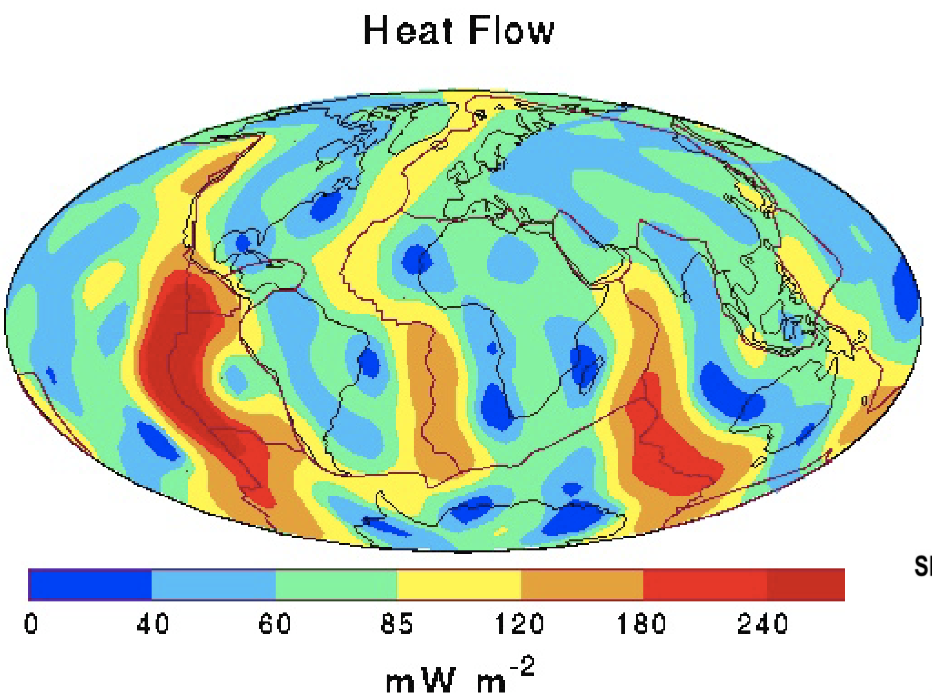


Energy flow from geo-thermal sources (radioactive decay)



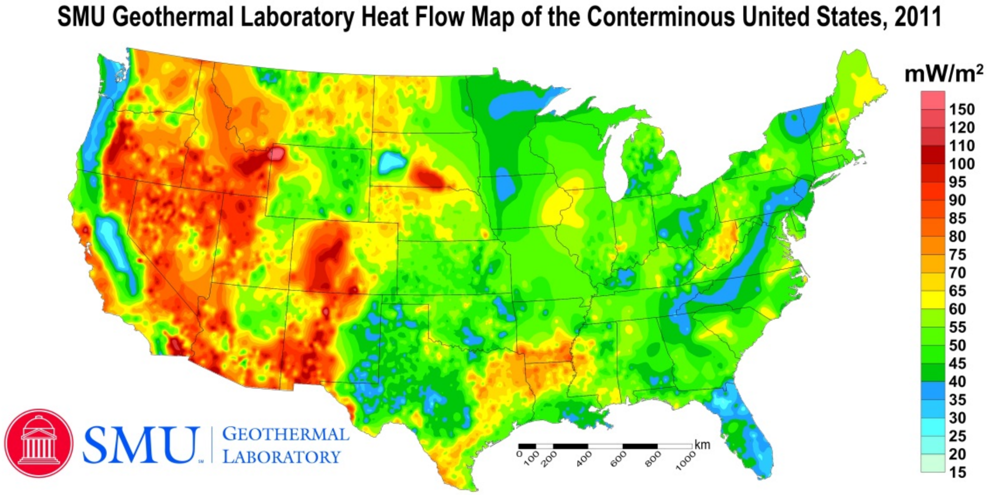
The Earth's internal thermal energy from radioactive decay (30 TW) and solar heating processes (14 TW) flows to the surface by conduction at a rate of 44 TW and can be utilized as energy source for human energy needs. Presently 28 GW of geothermal heating capacity is installed around the world, satisfying 0.07% of global primary energy consumption.

Global heat production rate



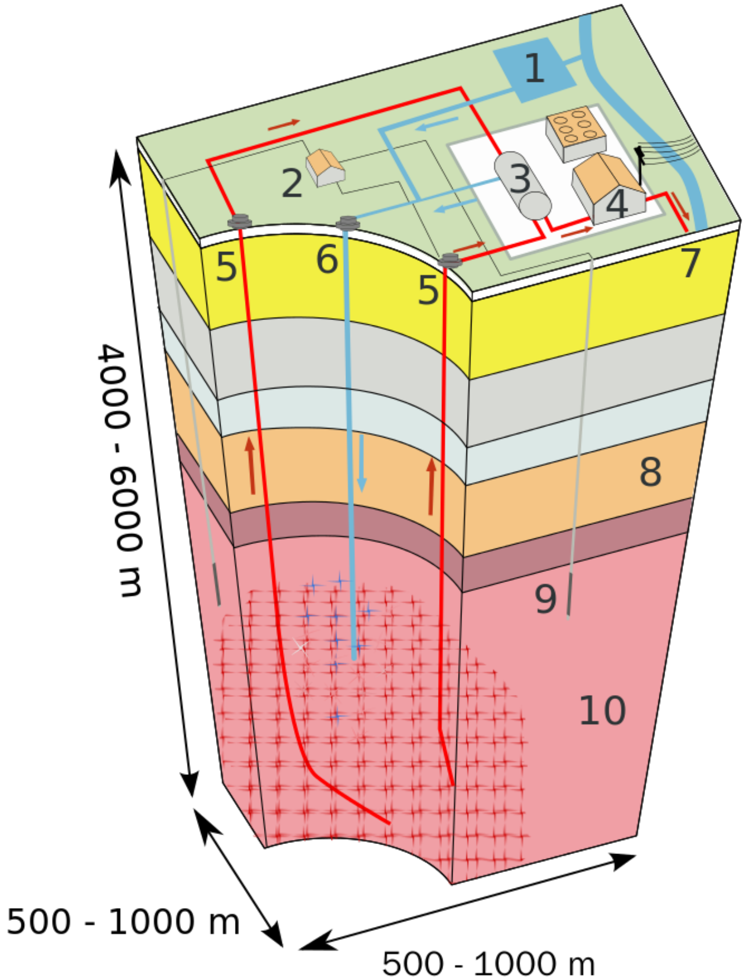
Heat flow is at maximum in the mid-ocean rift zones driving the continent shelves (hydrothermal vents)

US geothermal heat sources are located in the Western states, in particular Yellowstone area.



Reference: Blackwell, D.D., Richards, M.C., Frone, Z.S., Batir, J.F., Williams, M.A., Ruzo, A.A., and Dingwall, R.K., 2011, "SMU Geothermal Laboratory Heat Flow Map of the Conterminous United States, 2011". Supported by Google.org. Available at http://www.smu.edu/geothermal.

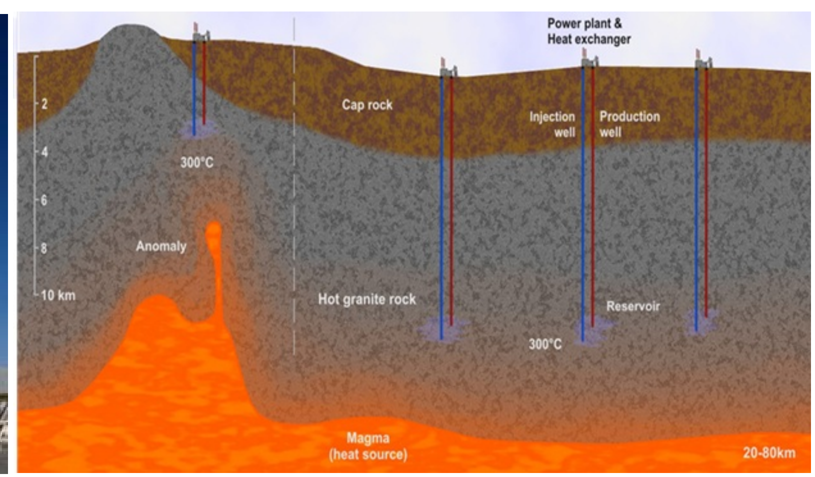
Utilization in areas with no natural water circulation



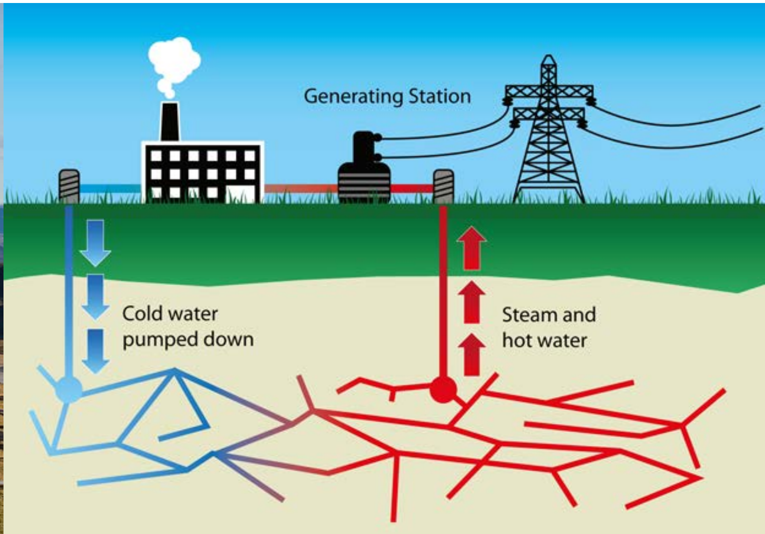
Enhanced geothermal system 1:Reservoir 2:Pump house 3:Heat exchanger 4:Turbine hall 5:Production well 6:Injection well 7:Hot water to district heating 8:Porous sediments 9:Observation well 10:Crystalline bedrock

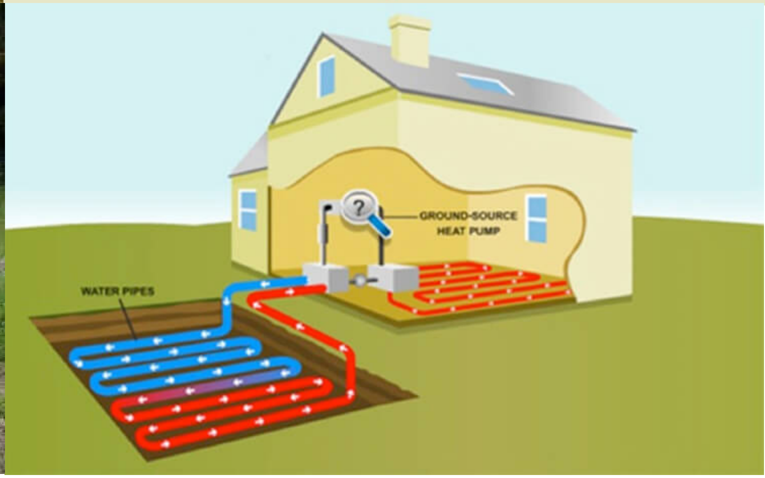
Requires deep down drilling for the installation of pipelines for high pressure cold water down into the porous hot layer and collecting and transferring hot water upwards.

Present depth of drilling for geothermal heat sources is a few hundred meters, proposed is to increase the depth to a few thousand meters. **On average, the geothermal gradient is around 25°C/km with peak values of 40°C/km.**



Geo-Thermal Energy





Direct water circulation is for large scale energy generation but causes transfer of radioactive material solutions to the surface. Indirect water circulation is less efficient, but has no radioactive material transfer component!

Radioactivity?

The problem is similar as with oil and gas industry, radioactive sediments are being flushed to the surface. Uranium and Thorium are not water solvable, but Radium may be solved in water, Uranium and Thorium may come as part of the scales and sludge.

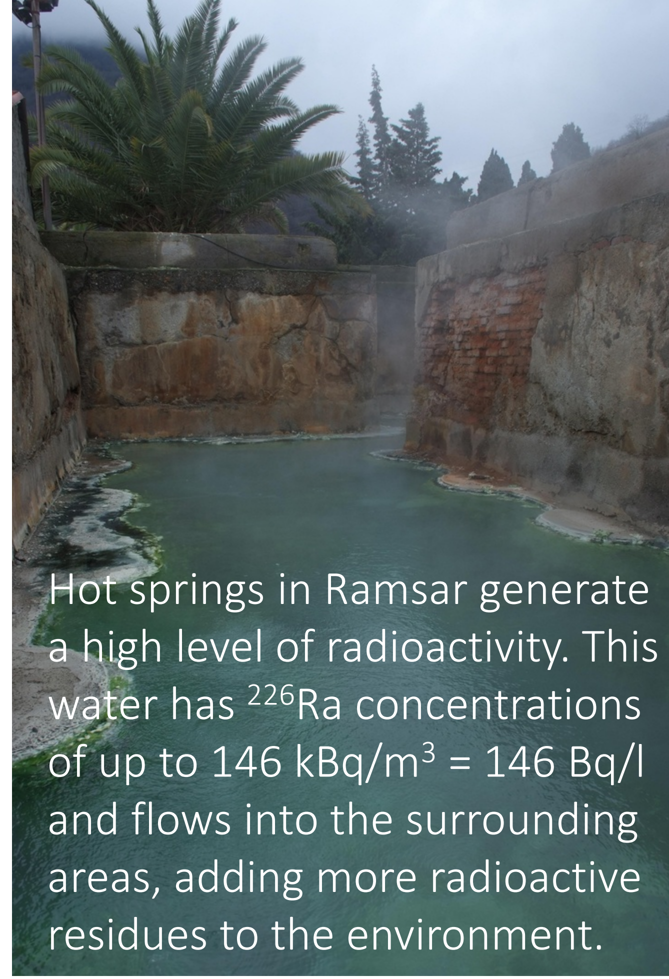
The levels in the soil and rocks vary greatly, as do their concentrations in scales and sludges. Radiation levels may vary from background soil levels to as high as several hundred picocuries per gram

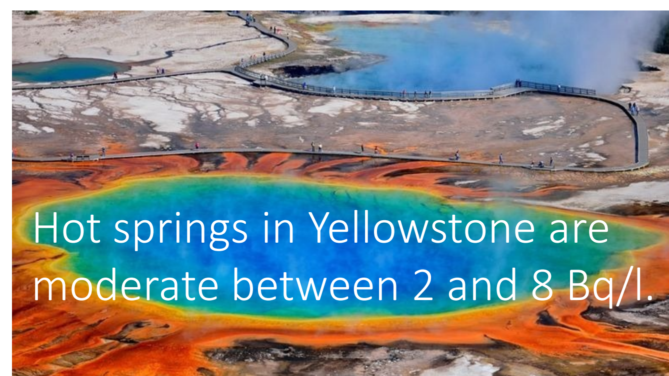
(pCi/g ≡ 37Bq/kg ≡ 37Bq/l).

The variation depends on several factors:

- Concentration and identity of the radionuclides.
- Chemistry of the geologic formation.
- Characteristics of the production process.

The radioactivity level in hot springs serves as good guide for estimating the range.

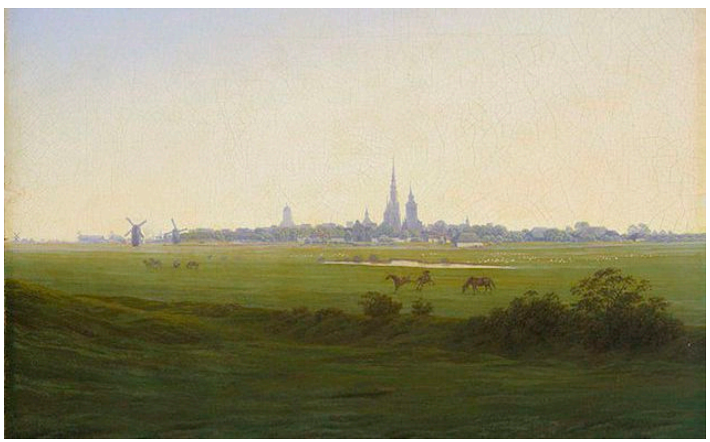




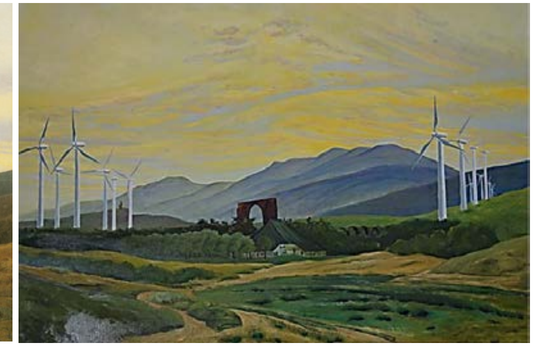
Wind Energy - the truly green energy

Frequently quoted environmental effects: noise of turbines, killing of birds, the visual blight!

The Visual Blight



On the example of the romantic painter
Caspar David Friedrich (1774-1840)

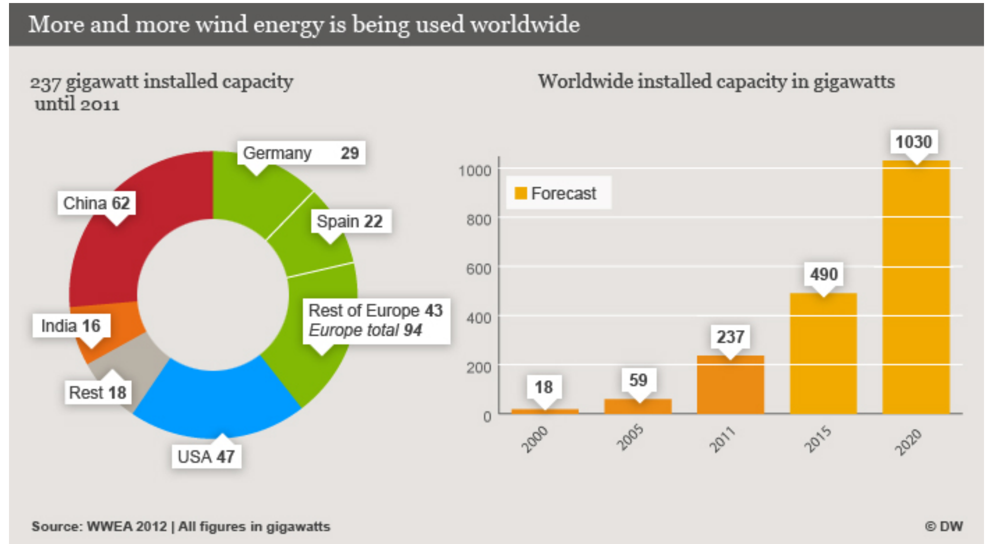


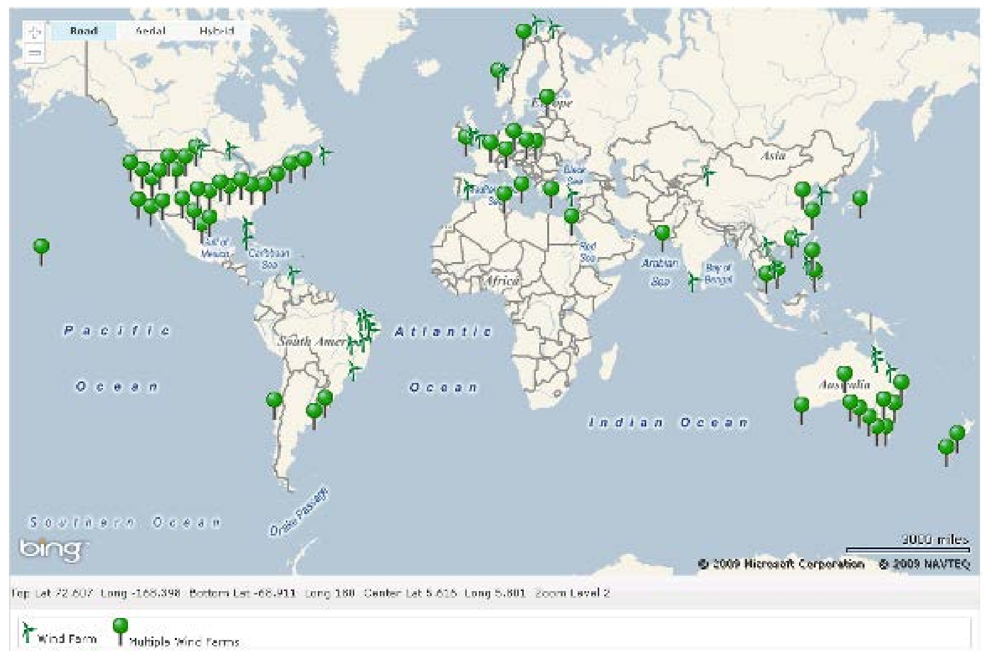
Areal requirements for wind power

A single wind energy turbine system produces 1500 – 3500 kW depending on wind speed, wind blade, and turbine characteristics. 1 GW power generation requires on average of 400 wind turbines with a required distance between turbines of 500 m.

Each turbine requires 250,000 m^2 area (for safety and wind efficiency reasons), this translates into an area of 10^8 m^2 = 100 km^2 = 40 square-miles!

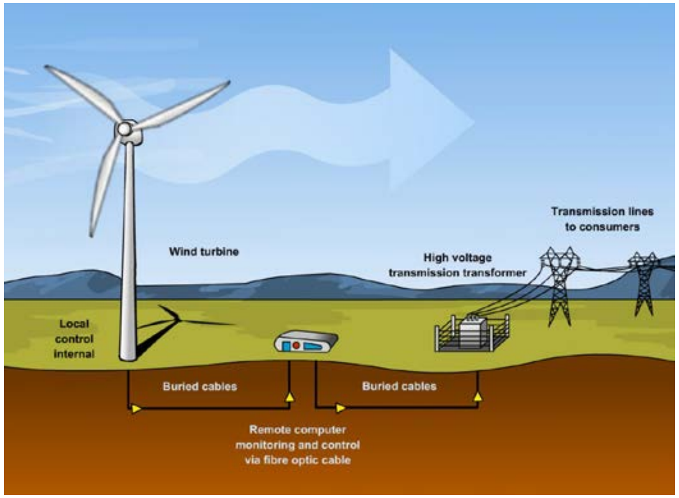
Wind power distribution

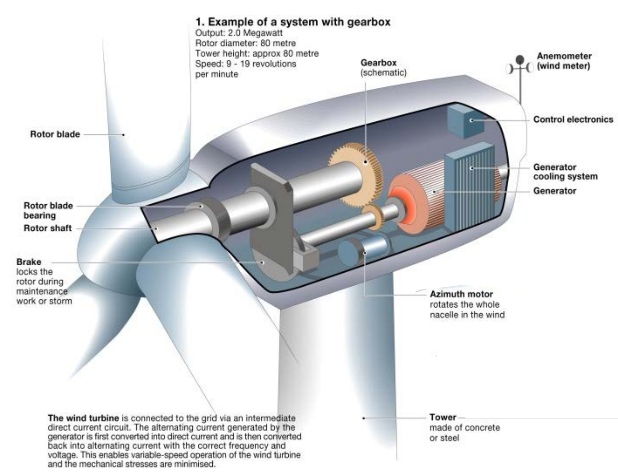


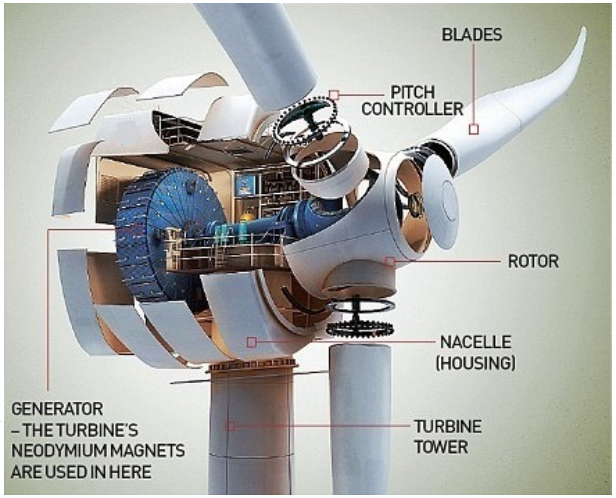


Energy transformation

Each wind turbine has a total of 2-7 blades or pallets to take the energy of the force of wind. The energy from the flowing air masses causes the windmills to spin, turning the energy of the wind into kinetic energy. The generator makes use out of the kinetic energy, turning it into electrical energy. Even though one wind turbine can power 600 households an hour, it is quite inefficient using only 40% of it efficiency.



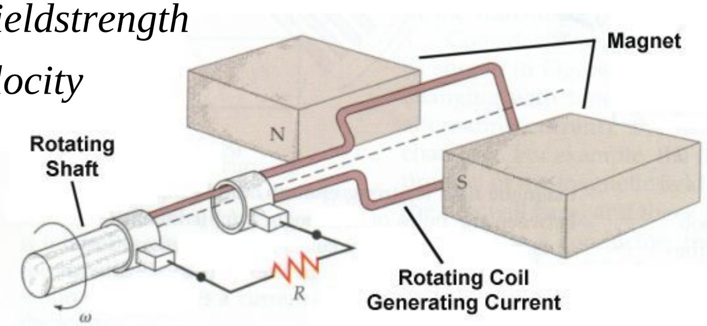




$$E = n \cdot B \cdot A \cdot \omega \cdot \sin \omega t \qquad E \equiv \textit{electrical potential} \qquad B \equiv \textit{magnetic fieldstrength}$$

$$E_{\max} = n \cdot B \cdot A \cdot \omega \qquad n \equiv \textit{coil windings of area } A \qquad \omega \equiv \textit{angular velocity}$$

A and n have limitations because of generator dimensions but the magnetic field strength $\mathbf{B}$ can be increased by the choice of the right "magnetic" materials: **Rare Earth Metals**



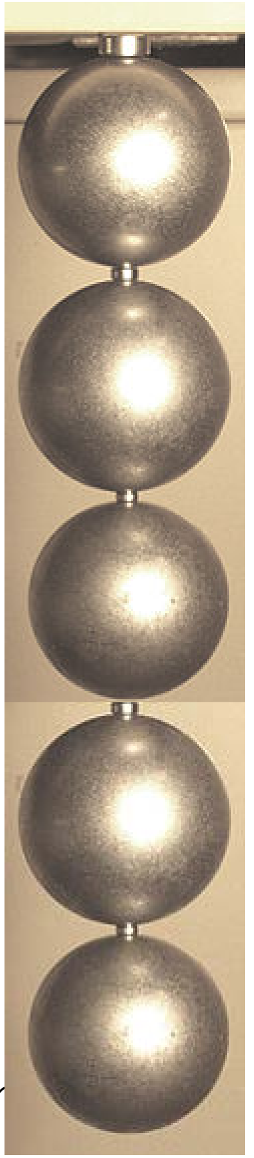
Rare Earth Metal Needs

Atomic Number	Element	Symbol
21	Scandium**	Sc
39	Yttrium	Y
57	Lanthanum	La
58	Cerium	Ce
59	Praseodymium	Pr
60	Neodymium	Nd
61	Promethium*	Pm
62	Samarium	Sm
63	Europium	Eu
64	Gadolinium	Gd
65	Terbium	Tb
66	Dysprosium	Dy
67	Holmium	Ho
68	Erbium	Er
69	Thulium	Tm
70	Ytterbium	Yb
71	Lutetium	Lu

Rare earth metals, yttrium, lanthanum or cerium are formed from 17 chemically similar elements and are extremely rare. Because of their strong magnetic properties and high electrical conductivity, they are light in weight and efficient, making them critical to the clean energy industry. Wind turbines, energy-efficient light bulbs, electric car batteries, and efficiency motors or generators all depend on dysprosium, neodymium and their other cousins to generate the magnets that make them work. So far no substitute has been found that can match rare earths in weight and efficiency.

Magnetic Materials

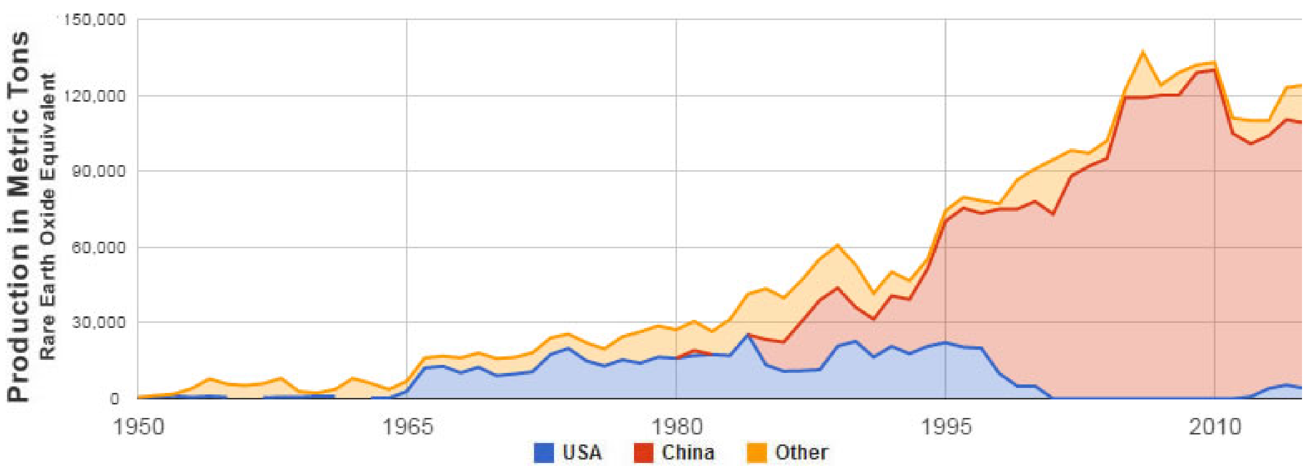
Magnet	Magnetic field (T)	Resistance to demagnetize (kA/m)	Energy Density (kJ/m^3)	Temperature Range	
				(°C)	(°F)
$Nd_2Fe_{14}B$ (sintered)	1.0–1.4	750–2000	200–440	310–400	590–752
$Nd_2Fe_{14}B$ (bonded)	0.6–0.7	600–1200	60–100	310–400	590–752
$SmCo_5$ (sintered)	0.8–1.1	600–2000	120–200	720	1328
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



Multiple applications of Rare Earth based materials in computer, informatior transportation and energy industries.

Rare Earth Economy

In 2000 China's low prices forced US producers out of business 2013 China dominated the production with 90%. With increase in prices and demands US and other countries created new mining initiatives!



United States Usage (2015 data from USGS)	
Chemical Catalysts	60%
Metallurgy & Alloys	10%
Ceramics and Glass Making	10%
Glass Polishing	10%
Other	10%

World Mine Production and Reserves (2015 Estimates)

Country	Production (Metric Ton)	Reserves (Metric Ton)
United States	4,100	1,800,000
Australia	10,000	3,200,000
Brazil	--	22,000,000
China	105,000	55,000,000
India	--	3,100,000
Russia	2,500	?
Thailand	2,100	not available
World total (rounded)	110,000	140,000,000

Clockwise from top center: praseodymium, cerium, lanthanum, neodymium, samarium, and gadolinium.

Rare Earth Element Harvesting

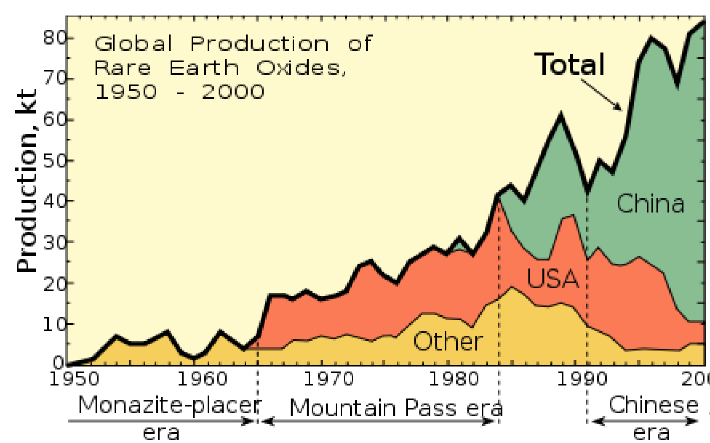
Rare earths are often located within minerals such as Bastnaesite, Monazite, Xenotime, and Thorite

The four Rare Earth containing minerals, Bastnaesite, Monazite, Xenotime, and Thorite, require special chemical treatment with acids to dissolve, extract and separate their basic elements.

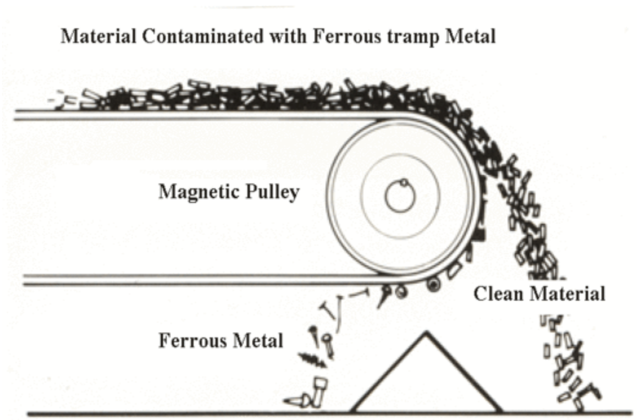
Biggest (and only) US Rare Earth Mining Facility

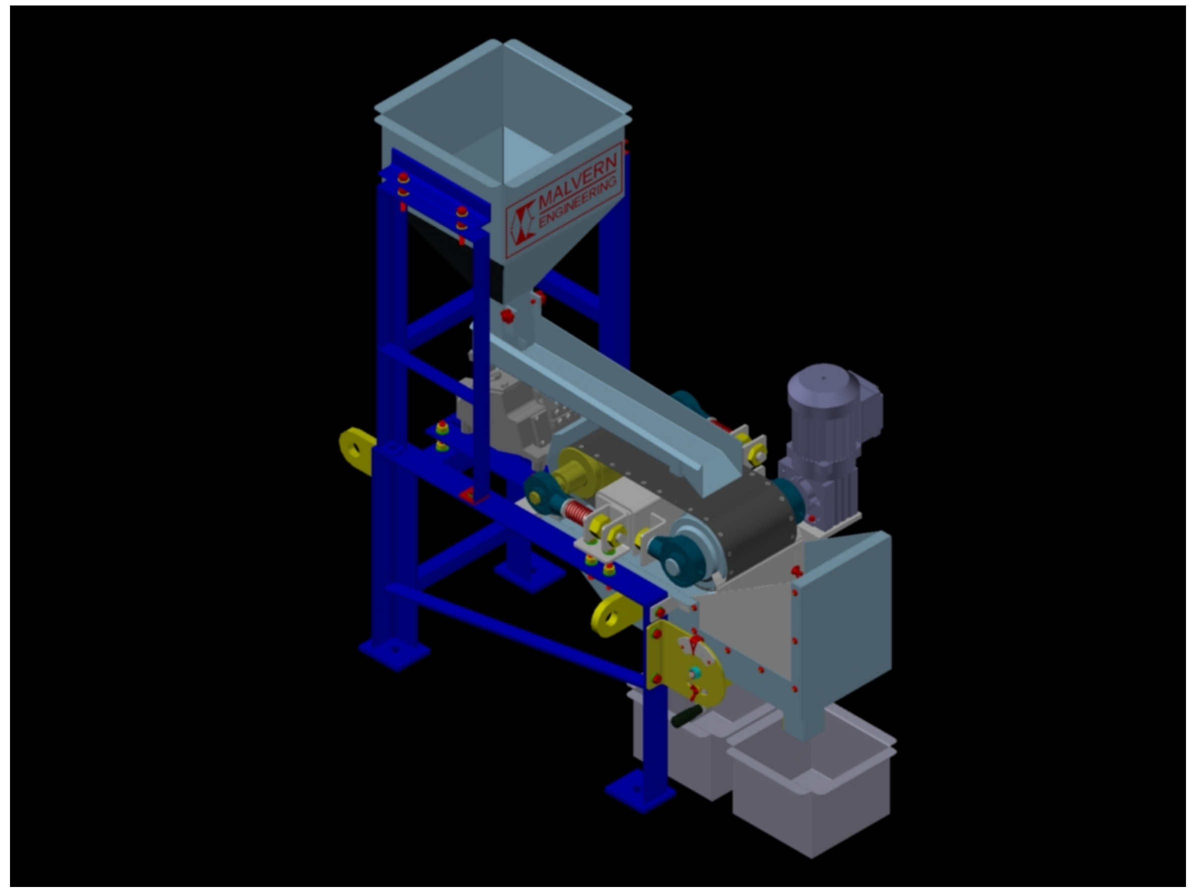
MolyCorp Minerals at Mountain Pass in the Mojave Desert in Nevada

The deposit was mined in a larger scale between 1965 and 1995 supplying most of the worldwide rare earth metals.
The mine closed in 2002, in response to both environmental restrictions and dropping prices.
The mine has been mostly inactive since 2002.
and MolyCorp declared bankruptcy in 2008



Magnetic Separation

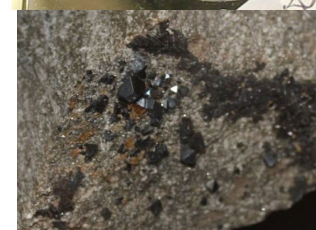




Magnetic ore (rare earth particles) stick to drum, and are separated into an extra container, the non-magnetic tailings are being removed. This can be a multi-step process with increasing purity

The Radioactive Footprint of Rare Earths

<ins>Bastnaesite</ins> is a rare earth fluoro-carbonate mineral containing cerium, lanthanum and yttrium as well as small amounts of all the rare earth metals and thorium. **The activity level is 400 Bq/kg from its ^{232}Th content!**



<ins>Monazite</ins> is normally cerium phosphate but the entire suite of rare earth metals including praseodymium, lanthanum, neodymium as well as thorium and uranium, are generally present in it. **The activity level is 6,000-40,000 Bq/kg from ^{238}U and 8,000-900,000 Bq/kg from ^{232}Th !**

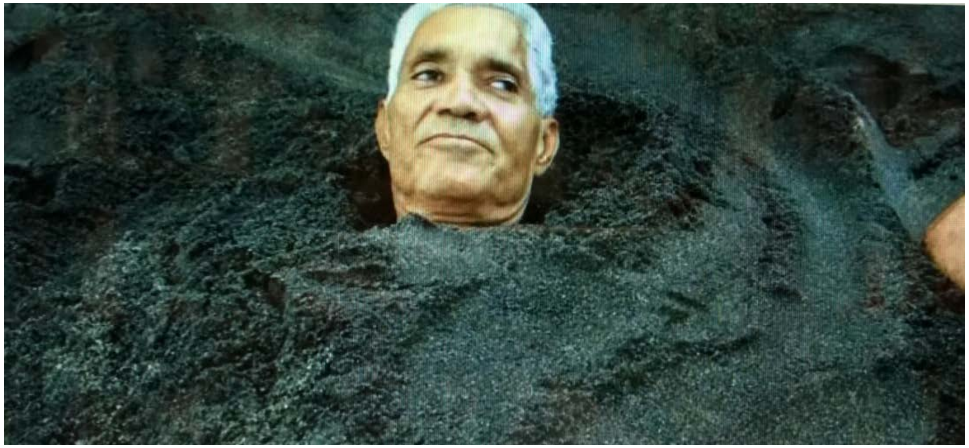
<ins>Xenotime</ins> is a phosphate of yttria, but also contains the rare earths of the cerium group. These minerals are exploited for the rare earths they contain, and especially for thorium and uranium. **The activity level is 3,500-500,000 Bq/kg from ^{238}U and 180,000 Bq/kg from ^{232}Th !**

<ins>Thorite</ins> is a silicate of thorium. It is the most common mineral of thorium and is nearly always strongly radioactive. **The activity level is 2,500,000-5,500,000 Bq/kg from its ^{232}Th content!**

Beaches of Brazil

Monazite enriched black sand washed down from the mountains along the shore lines contains significant amounts of Thorium! The reading is μSv/h.

The locals believe in the healing powers of the Monazite black sands!



Radioactive Waste from Rare Earth Processing

Artificial toxic, radioactive lake deposition in Malaysia, Mongolia and China, such as in **Baotou lake**

The mining of one ton of rare earth minerals produces about one ton of radioactive waste, assuming an average of 40,000 – 400,000 Bq/kg (very crude estimate since no data available) a ton of rare earth materials generate 0.4-4.0 GBq on radioactive waste being dumped into artificial lakes.

The radioactive foot print of windmills

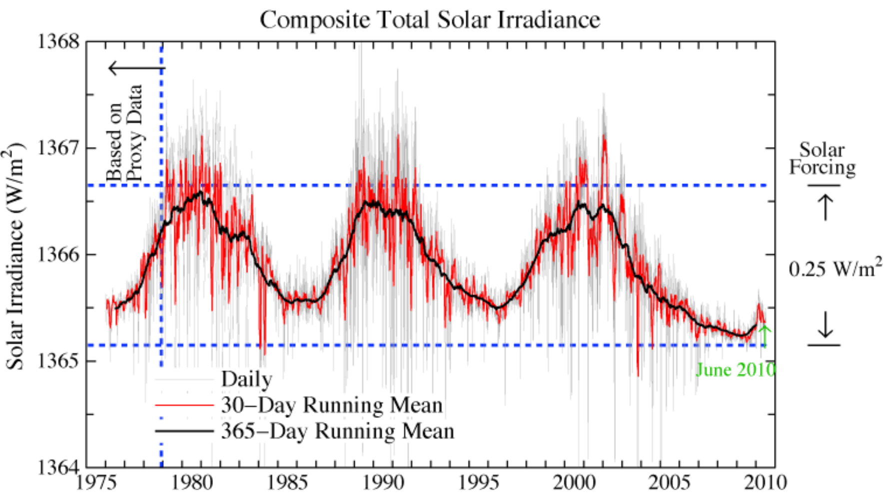
A 2 megawatt (MW) wind turbine contains about 800 pounds of neodymium and 130 pounds of dysprosium, which is mostly harvested and processed in China.

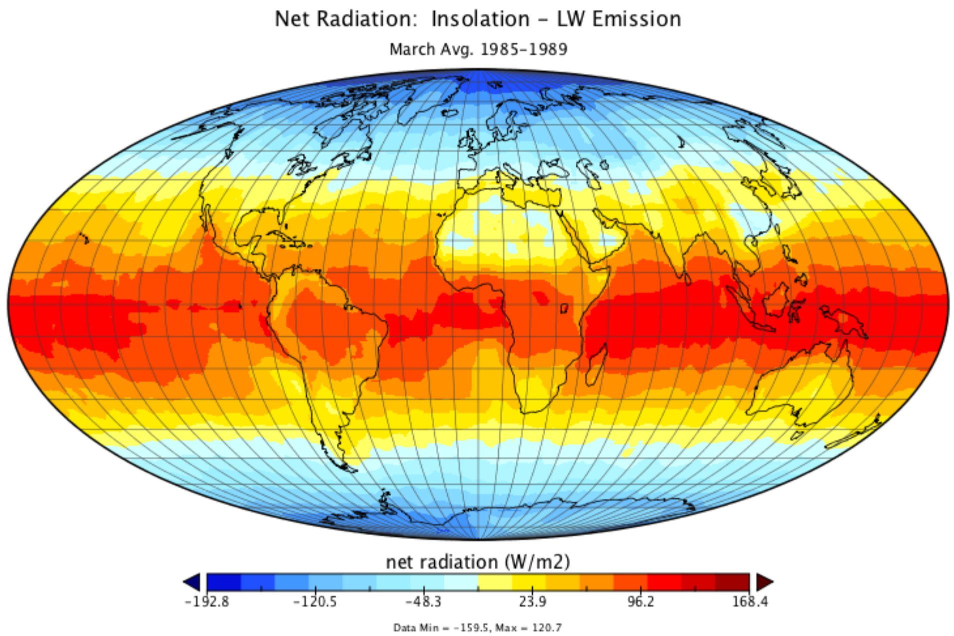
- The mining of one ton of rare earth minerals produces about one ton of radioactive waste.
- Each year, the U.S. adds a record 10 – 15 GW of wind generating capacity.
- That translates to about 5 million pounds of rare earths in newly installed wind turbines.
- Consequently 5 million pounds of radioactive waste were created in the harvesting process.
- In comparison, America's nuclear industry produces around 5 million pounds of spent nuclear fuel each year.
- nuclear energy provides about 20% of America's energy needs, wind accounts for just 4%.

Solar Energy

Solar thermals systems:	convert sunlight into heat
Solar photovoltaic systems:	convert sunlight into electricity

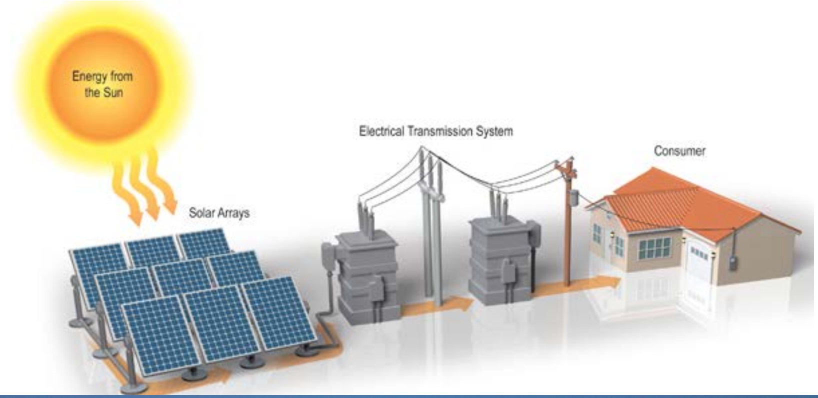
Power production by solar energy





High power generation requires large areas; 1 GW of total irradiance requires an area 732,000m^2 or 0.73 km^2 if all the sunlight is converted to energy. Irradiance in the US is typically near 50-60% of total irradiance. The photovoltaic efficiency of conversion is 20%. This ten folds the required area to 7.3 km^2 or 3 square-mile, an order of magnitude improvement over wind power.

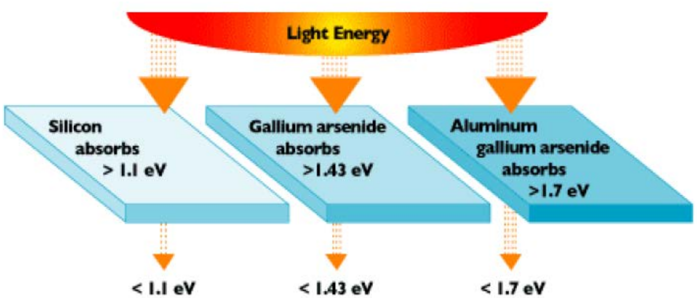
Photovoltaic plants

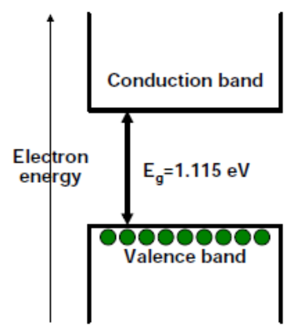


Require a lot of space and a lot of sun-light

The photovoltaic effect

A photovoltaic (PV) cell corresponds to two semi-conductor materials n (negative) and p (positive type are sandwiched together. The photovoltaic effect occurs when photons release electrons near the np-junction from the valence band to the conducting band in the lattice of a semi-conductor material Si, Ge, GaAs , etc. The electric charges are moved by an internal electrical potential at the semi-conductor junction, creating an electric current that is proportional to the amount of absorbed light intensity. An individual PV cell is usually small, typically producing about 1 or 2 watts of power. For producing energy for a 60 W light bulb, about 100 PV cells need to be matched together.





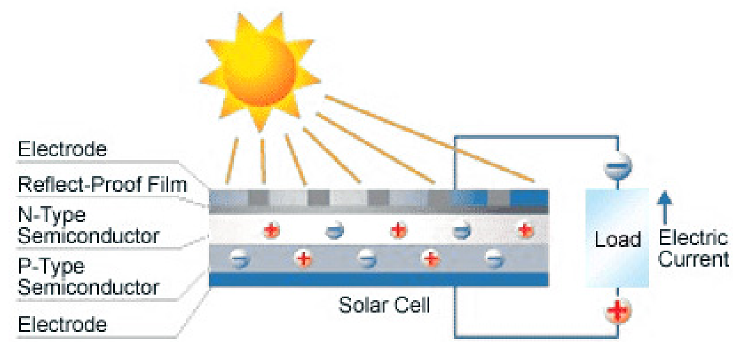
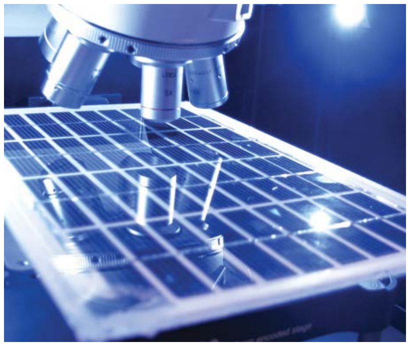


Table II. Confirmed terrestrial module efficiencies measured under the global AM1.5 spectrum (1000 W/m^2) at a cell temperature of 25 °C (IEC 60904-3: 2008, ASTM G-173-03 global).

Classification	Effic. (%)	Area (cm^2)	V_{oc} (V)	I_{sc} (A)	FF (%)	Test centre (date)	Description
Si (crystalline)	22.9 ± 0.6	778 (da)	5.60	3.97	80.3	Sandia (9/96)[a]	UNSW/Gochermann [32]
Si (large crystalline)	22.4 ± 0.6	15 775 (ap)	69.57	6.341[b]	80.1	NREL (8/12)	SunPower [33]
Si (multicrystalline)	18.5 ± 0.4	14 661 (ap)	38.97	9.149[c]	76.2	FhG-ISE (1/12)	Q-Cells (60 serial cells) [34]
GaAs (thin film)	24.1 ± 1.0	858.5 (ap)	10.89	2.255[d]	84.2	NREL (11/12)	Alta Devices [35]

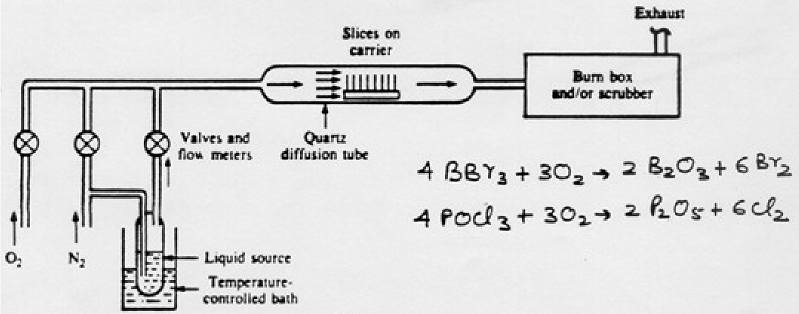


N-type, P-type semiconductors

In **n-type semiconductors**, electrons are the majority carriers and holes are the minority carriers. **N-type semiconductors** are created by doping an intrinsic **semiconductor** with donor impurities. A common dopant for **n-type** silicon is phosphorus. It has free valence electrons that can be easily released enhancing the production of free electrons.

Phosphorus can be added by diffusion of phosphine PH_3 gas. Bulk doping can be achieved by implantation or by nuclear transmutation, by irradiation of pure silicon with neutrons in a nuclear reactor.

P-Type Semiconductor. The addition of trivalent impurities such as boron, aluminum or gallium to an intrinsic **semiconductor** creates deficiencies of valence electrons, called "holes". It is typical to use B_2H_6 diborane gas to diffuse boron into the silicon material.



Phosphorus oxy chloride

$$4POCl_3 + 3O_2 \rightarrow 2P_2O_5 + 6Cl_2$$

Phosphine

$$2PH_3 + 4O_2 \rightarrow P_2O_5 + 3H_2O$$

$$2P_2O_5 + 5Si \Leftrightarrow 4P + 5SiO_2$$

Diborane

$$B_2H_6 + 3O_2 \xrightarrow{300^\circ C} B_2O_3 + 3H_2O$$

$$B_2H_6 + 6CO_2 \longrightarrow B_2O_3 + 3H_2O + 6CO$$

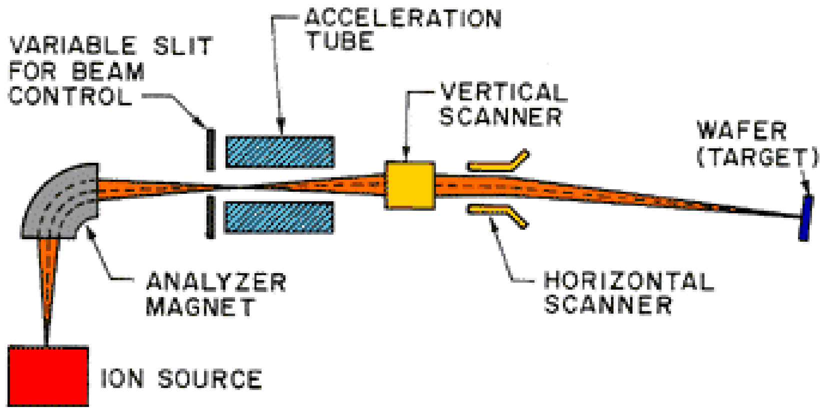
Boron Tribromide

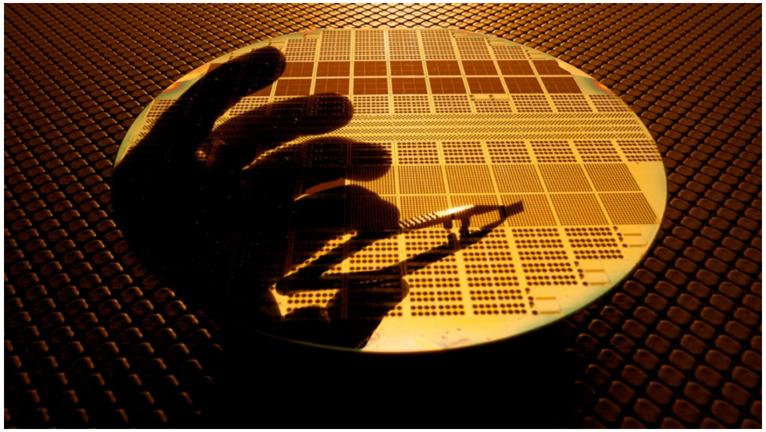
$$4BBr_3 + 3O_2 \rightarrow 2B_2O_3 + 6Br_2$$

$$2B_2O_3 + 3Si \Leftrightarrow 4B + 3SiO_2$$

Ion Implantation

The ion beam is produced in an ion source by plasma ionization of sputtering, extracted and separated by mass and charge in a magnetic field, accelerated and implanted in Si wafers. This approach is not for mass production!



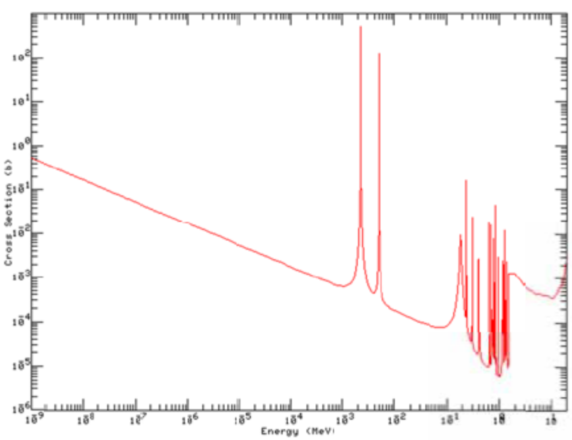


Neutron activation of rare isotope components

with subsequent decay to doping material

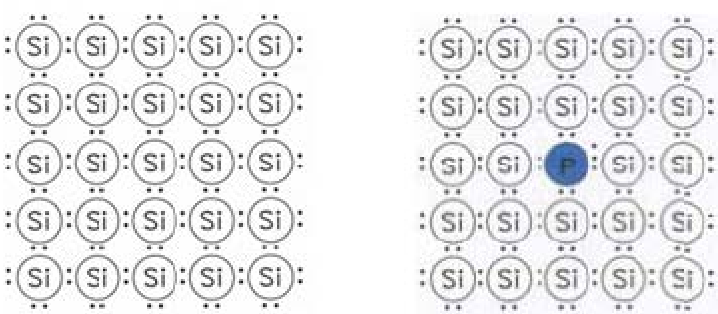
$$^{30}Si(n,\gamma)^{31}Si(\beta^-)\,^{31}P \quad ^{30}Si\text{: } 3.1\%$$

Similar neutron activation processes at other semiconductor materials



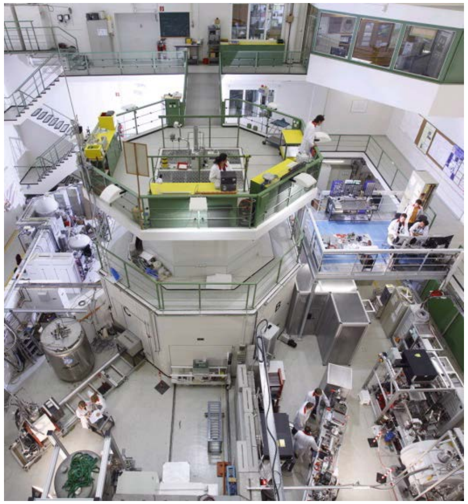
Neutron capture cross section of ^{30}Si

Reaction probability or cross section requires thermal neutron energies!

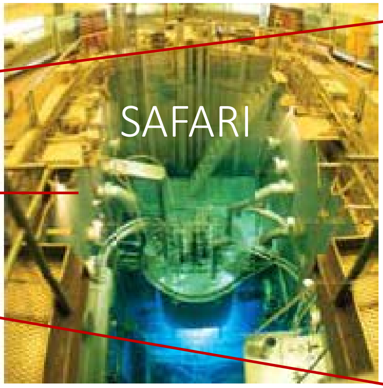


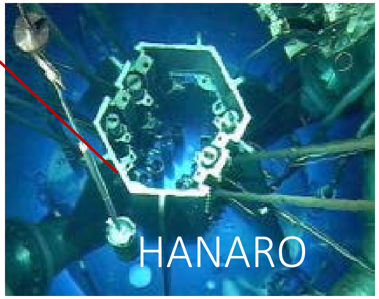
^{30}Si isotope in Si lattice is converted to ^{31}P

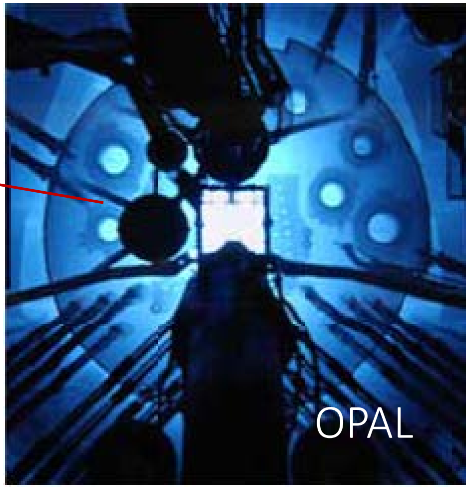
Utilization of Nuclear Reactors for efficient production of Solar Energy



Reactor	Thermal power	Irradiation rig	Neutron flux [$cm^{-2}s^{-1}$]	Gamma ray heating or temperature
MARIA in Poland	30 MW		2.1×10^{13}, (thermal), Fast (>1 MeV)/thermal=0.02	0.5 W/g
BR2 in Belgium	56 MW (Nominal: 85 MW)		1.74×10^{14} (thermal), 1.9×10^{13} (fast),	< 200°C Si core temp.
SAFARI-1 in South Africa	20 MW	4 inch SILIRAD	2.5×10^{13}-8×10^{13} (thermal)	Measured temperature at Si: ~80°C
FRM II in Germany	20 MW	8 inch	1.6×10^{13} (thermal) Thermal/fast=1700	Max. temp.: 110°C (Si core temp.) [44]
OPAL in Australia	20 MW	5, 6, 8 inch	2.5×10^{12} – 1.5×10^{13} (thermal) Thermal/fast=900	
HANARO in the Republic of Korea	30 MW	5,6 inch NTD2	Thermal/fast=400 Cd ratio for gold: 16~22	0.2–0.9 W/cm^3







Smaller scale reactors (TRIGA type) that don't generate much energy, but a relatively high neutron flux between 10^{12} and 10^{14} neutrons/cm^2/s!

Why not direct Nuclear? ☺