School of Engineering

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Renewable Energy 1: Solar and Geothermal (EG501J)

Geothermal Energy:

General Overview of the Energy Mix

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September 2014

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Outline

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(Hellisheiði Geothermal Power Station)

- Energy Consumption
- Economics of Geothermal Energy
- Basics of a Power Plant
- Current Commercial Power Plants
- Future Reactor Designs

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Energy: Production & Demand








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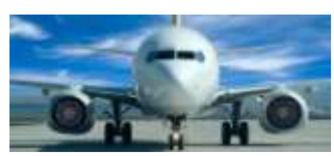
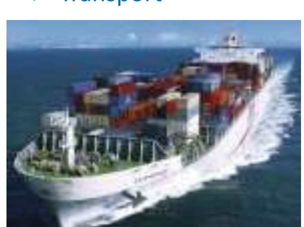
Overview of the Energy Industries



We use energy to provide:

- Electricity
- Heat
- Transport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Overview of the Energy Industries

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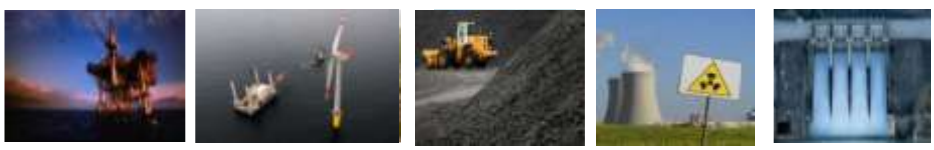
From:
- Fossil fuels:
  - Oil;
  - Gas;
  - Coal;
- Nuclear;
- Hydroelectricity;
- Wind;
- Solar;
- Maritime (wave, tide etc);
- Geothermal;
- Etc.



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Overview of the Energy Industries

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Major Issues:
- Rising energy demand;
- Need to stabilise atmospheric CO_2 at 550ppm;
- Aging fleet of coal & nuclear plant;
- Concerns about storage of nuclear waste;
- Declining oil & gas reserves 30- 50 years;
- Only 70 years of uranium left;
- Reduce reliance on hydrocarbons.

Policy drivers:
- Low Carbon Society;
- Security of Supply;
- Fuel Poverty;

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Growth Trends (1985-2010):

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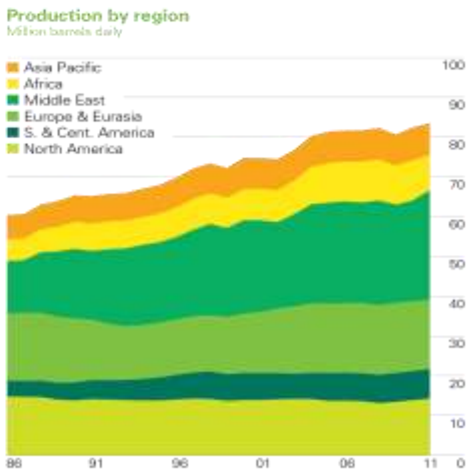
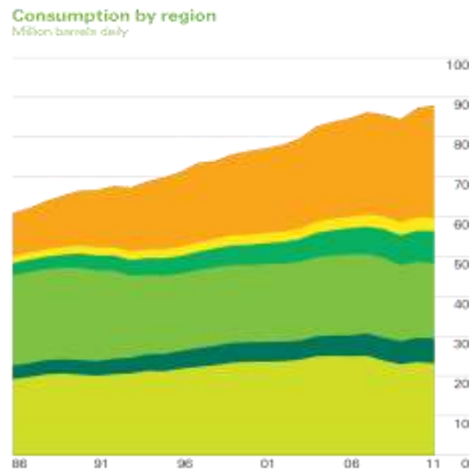
Oil Production/Consumption





World oil production increased by 1.1 million b/d in 2011, with OPEC accounting for nearly all of the increase despite a 1.2 million b/d reduction in Libyan production. The US had the largest growth in non-OPEC supply for a third consecutive year. World oil consumption increased by roughly 600,000 b/d. All of the net growth came from emerging economies in Asia, South & Central America, and the Middle East, offsetting declines in Europe and North America.

Source: BP Statistical Review of World Energy (2012)

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Growth Trends (1985-2010):

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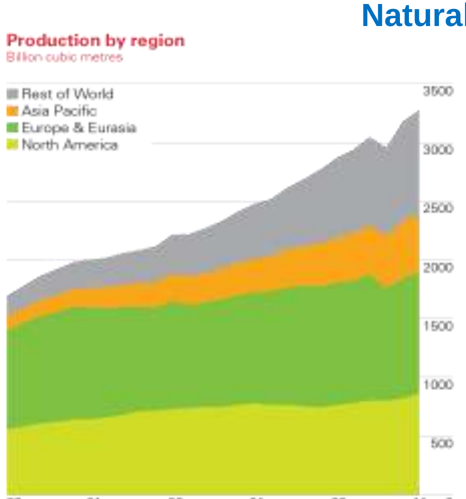
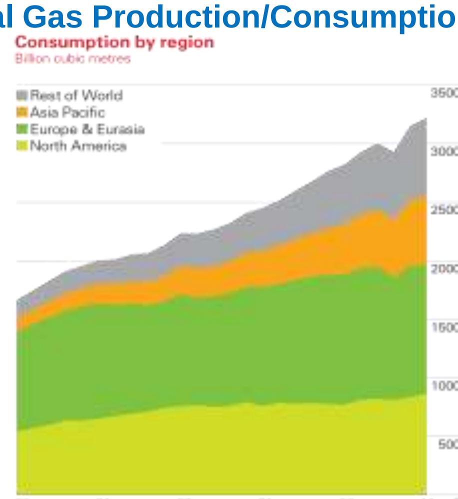
Natural Gas Production/Consumption





World natural gas production increased by 3.1% in 2011. While the US saw the largest national increase, the Middle East recorded the largest regional increment to production. Production growth in Russia and Turkmenistan was partly offset by a large decline in European production. Natural gas consumption increased by 2.2%, with below-average growth in all regions but North America. The European Union experienced the sharpest decline in natural gas consumption (–9.9%) on record.

Source: BP Statistical Review of World Energy (2012)

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Growth Trends (1985-2010):

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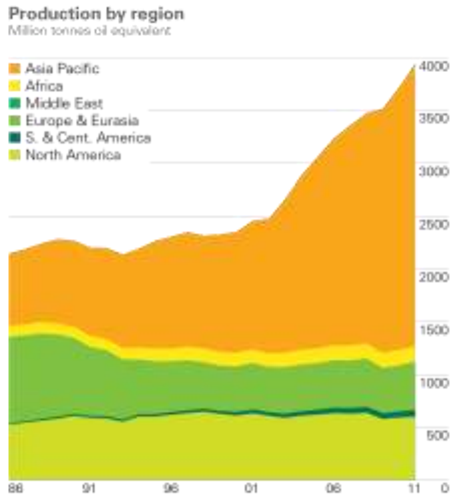
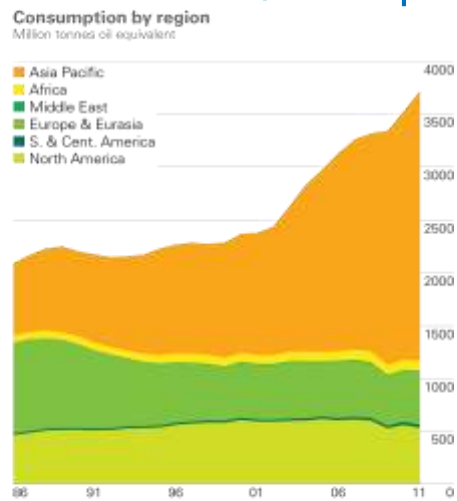
Coal Production/Consumption





Coal was again the fastest-growing fossil fuel. Global production grew by 6.1%. The Asia Pacific region accounted for 85% of global production growth, led by an 8.8% increase in China, the world's largest supplier. Global coal consumption increased by 5.4%, with the Asia Pacific region accounting for all of the net growth. Elsewhere, large declines in North American consumption were offset by growth in all other regions.

BP Statistical Review of World Energy 2012
© BP 2012

Growth Trends (1985-2010):

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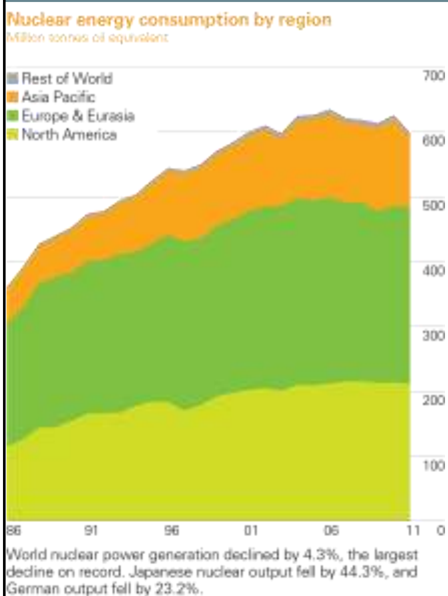
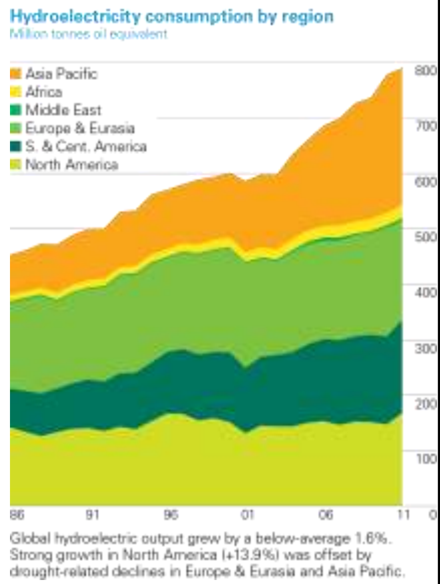
	Production 2010	Historical Growth	Growth(%)
Oil	86M mbo/day	1M mbo/year	1.2
Coal	3.6B Toe	160M toe/year	4.4
Gas	3150B m^3	60B m^3/year	1.9

toe: Tonnes oil equivalent
mbo: million barrel of oil

1 toe = 11.63 MWh = 41.87 GJ = 39.7M BTU
1 toe = 7.4 barrel of oil equivalent (boe)
1 barrel of oil = 159 litres

Growth Trends (1985-2010):





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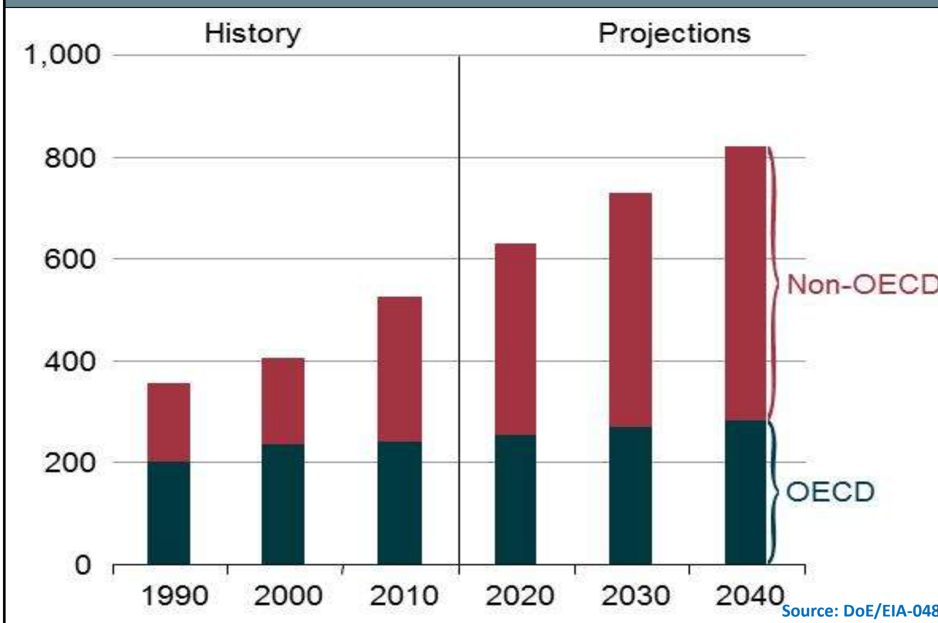
World Energy Consumption (10^{15} BTU)



Source: DoE/EIA-0484

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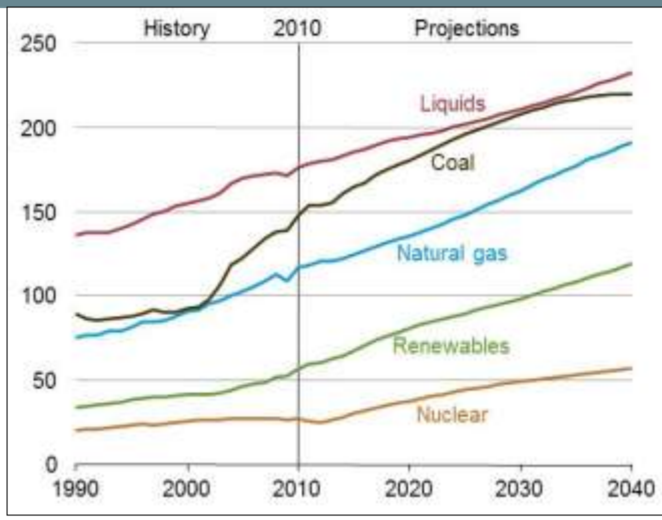
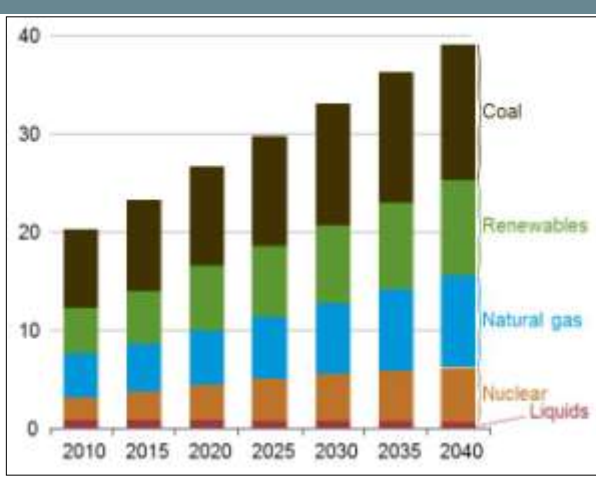
World Energy Consumption (fuel type, 10^{15} BTU)



Source: DoE/EIA-0484

- Petroleum liquids fuels: crude oil and lease condensate, natural gas plant liquids, bitumen, extra-heavy oil, and refinery gains;
- Other liquids fuels: gas-to-liquids, coal-to-liquids, kerogen and biofuels.

World Net Electricity Generation (fuel type, 10^{12} kWh)



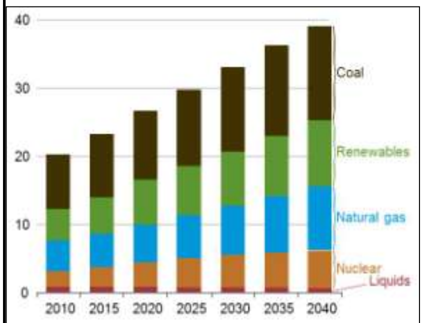
Variation (2010-40):

Liquids	-1.0 %
Nuclear	2.5%
Natural Gas	2.5%
Renewables	2.8%
Coal	1.8%
WORLD	2.2%

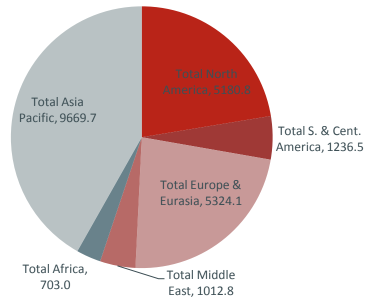
Conversion: 1 kWh = 3412.15 BTU

Source: DoE/EIA-0484

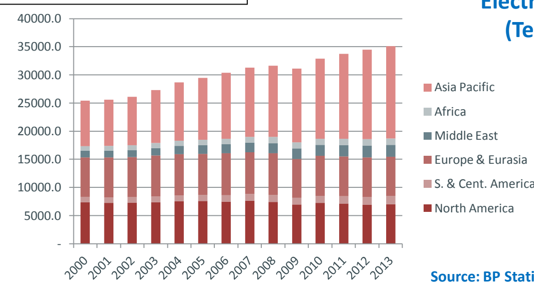
World Energy



World electricity generation (10^{12} kWh)



Electricity Generation (Terawatt-hours)

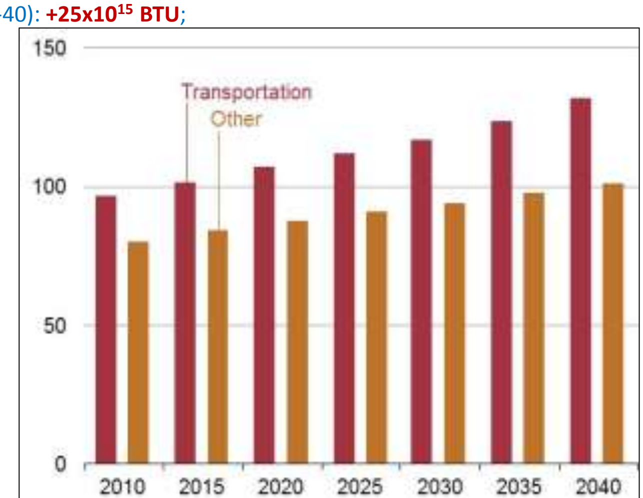


CO_2 Emissions (Million tonnes)

Source: BP Statistical Review of World Energy (2014)

World liquid consumption (10^{15} BTU)

- Petroleum and other liquid fuels are the main component of energy sector energy;
- Transport accounts for 63% of total growth in energy consumption over 2010-40;
- Transport Sector (2010-40): **+36x10^{15} BTU**;
- Industry Sector (2010-40): **+25x10^{15} BTU**;



Source: DoE/EIA-0484

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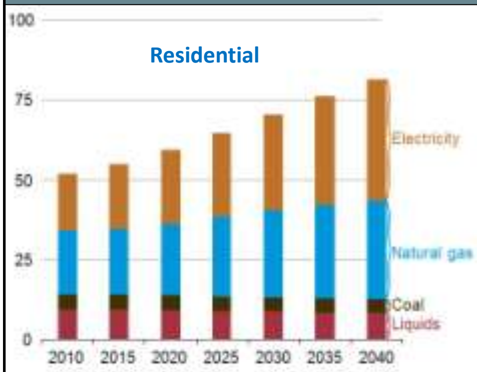
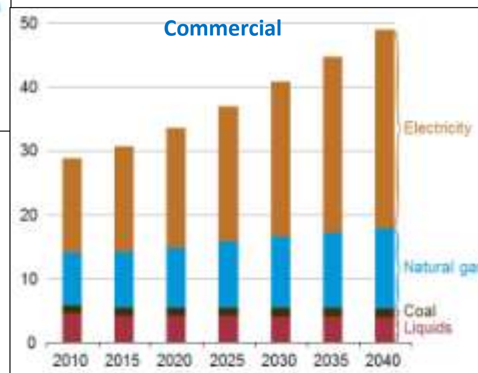
World Residential/Commercial Consumption (10^{15} BTU)





Source: DoE/EIA-0484

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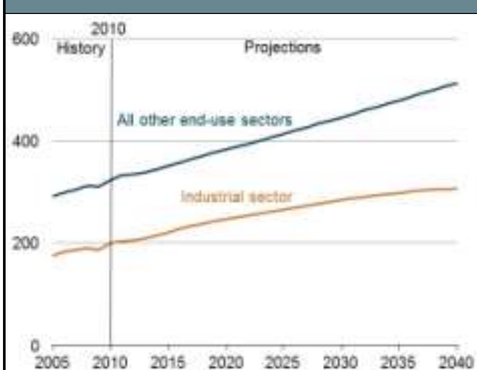
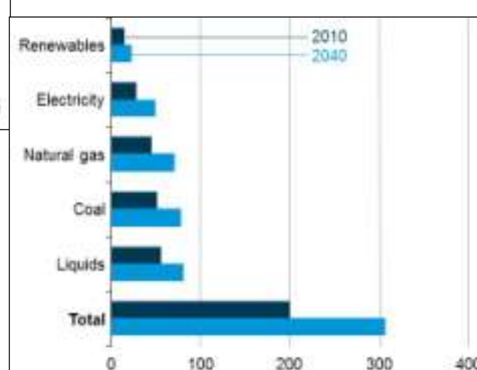
World Industrial Sector Consumption (10^{15} BTU)





Source: DoE/EIA-0484

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Energy Consumption: Transport Sector (10^{15} BTU)

Region	2010	2015	2020	2030	2040	Aver. Annual % change
OECD	**57.9**	**56.0**	**55.9**	**54.5**	**55.5**	**-0.1**
Americas	32.7	32.5	32.5	31.7	32.9	0.0
Europe	18	16.3	16.2	15.7	15.7	-0.5
Asia	7.1	7.2	7.1	7.0	7	-0.1
Non-OECD	**43.1**	**50.3**	**56.4**	**68.3**	**83.9**	**2.2**
Europe and Euroasia	6.7	8.0	8.5	9.5	10.6	1.5
Asia	19.9	23.5	28.0	37.0	49.2	3.1
Middle-East	6	7.4	8.1	8.6	9.5	1.5
Africa	3.8	4.0	4.1	4.5	4.8	0.8
Central and South America	6.6	7.3	7.7	8.8	9.8	1.3
TOTAL	**101.0**	**106.2**	**112.2**	**122.8**	**139.5**	**1.1**

Energy used to move people and goods by road, rail, air, water and pipeline.

Source: DoE/EIA-0484

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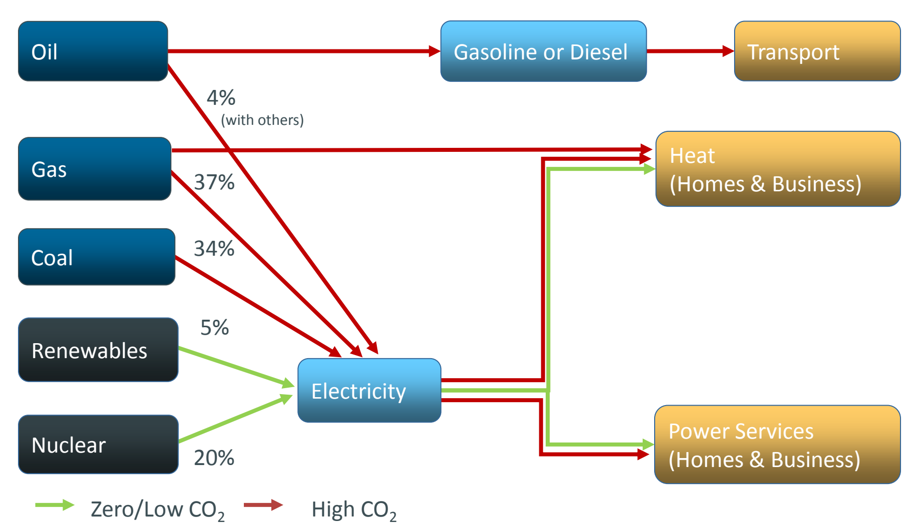
Energy Mix in UK



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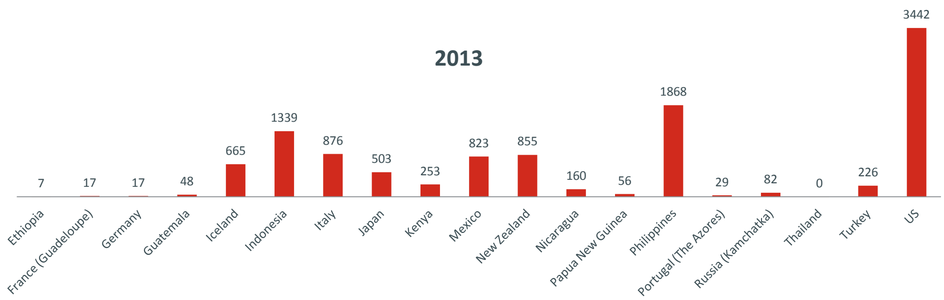
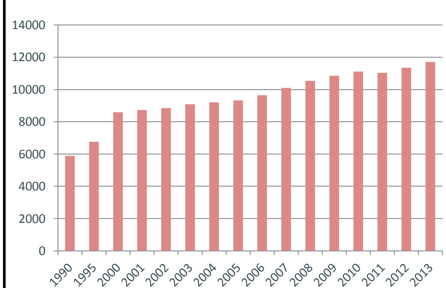
Geothermal Power Capacity (MW) Cumulative Installed





- Nearly 12GW supplied to 24 countries worldwide;
- Electricity attends the need of more than 60M people;
- Indonesia: 23% of all electricity generated by geothermal sources and;
- Iceland: Fully powered by renewables with geothermal producing 17% of the electricity and 87% of the heating;

Source: BP Statistical Review of World Energy (2014)

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10 Largest Power Plants of the World (2011)

Rank	Plant	Country	Capacity (MW_{el})	Aver. Annual Elect. Gen. (TWh)	Plant Type
1	3-Gorges Dam	China	22500	98.1	Hydro
2	Itaipu Dam	Brazil/Paraguay	14000	98.2	Hydro
3	Guri Dam	Venezuela	10235	53.41	Hydro
4	Tucurui Dam	Brazil	8370	21.4	Hydro
5	Kashiwaazaki-Kariwa NPP	Japan	8212	24.63	Nuclear
6	Grand Coulee Dam	USA	6809	21	Hydro
7	Longtan Dam	China	6426	18.7	Hydro
8	Bruce NPP	Canada	6272	36.25	Nuclear
9	Uljin NPP	South Korea	6157	44.81	Nuclear
10	Yeonggwang NPP	South Korea	6139	48.16	Nuclear

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Largest Power Plants by Energy Source (2011)

Rank	Plant	Country	Capacity (MW_{el})	Plant Type
1	3-Gorges Dam	China	22500	Hydro
2	Kashiwaazaki-Kariwa NPP	Japan	8212	Nuclear
3	Taichung Power Plant	Taiwan	5780	Coal
4	Shoaiba Power Plant	Saudi Arabia	5600	Fuel Oil
5	Surgut-2 Power Plant	Russia	5597	Natural Gas
6	Eesti Power Plant	Estonia	1615	Oil Shale
7	Shatura Power Plant	Russia	1500	Peat
8	Alta Wind Energy Center	USA	1020	Wind (onshore)
9	Tilbury B Power Station	UK	750	Biofuel
10	**Hellisheioi Power Station**	**Iceland**	**303**	**Geothermal**
11	Sihwa Lake Tidal Power Station	South Korea	254	Tidal
12	Agua Calient Solar Project	USA	251	Solar
13	Agucadora Wave Farm	Portugal	2	Marine (wave)

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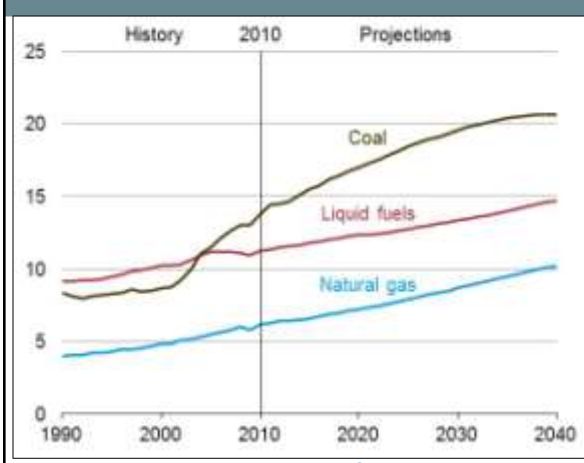
World Energy-related CO_2 Emissions (in billion metric tons)



Source: DoE/EIA-0484

1 cubic ton =40 cubic feet = 1.133 cubic meters

- Increase of coal power stations → Increase coal consumption → more GHC (Greenhouse gases);
- Growth in consumption of liquid fuels and natural/shale gas over the next 30 years;
- Solar, wind, biomass (renewables) will benefit from intensive R&D and will continue to grow, but;
- Solar and wind: unlikely to produce more than 25% of world demand of electricity by 2050.

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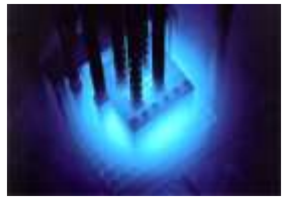

Energy Conversion: Reapplication of Fundamental Physics

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Why Geothermal (or why pursue a diverse energy matrix)??

- To address **CLIMATE CHANGE** we must:
  - ✓ improve efficiency and;
  - ✓ reduce use of fossil fuel-based energy source.
- GHG emissions should be mitigated by the development of new cost-effective technologies:
  - ✓ Carbon Capture Storage and Transportation (CCST);
  - ✓ Nuclear →Management of nuclear waste storage;
  - ✓ Low-carbon energy sources (i.e., renewables);
  - ✓ Integrated Gasification Combined Cycle (IGCC):
    - Converting carbon-based fuels into syngas (gas-synthesis - mainly H_2, CO);
    - Combined steam (e.g., Rankine) and gas (e.g., Brayton) cycles using advanced turbines with high thermal efficiency;
- Energy security: most countries do not have fossil-fuel resources to sustain their economies.

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How Power Plants Work? Heat Sources!

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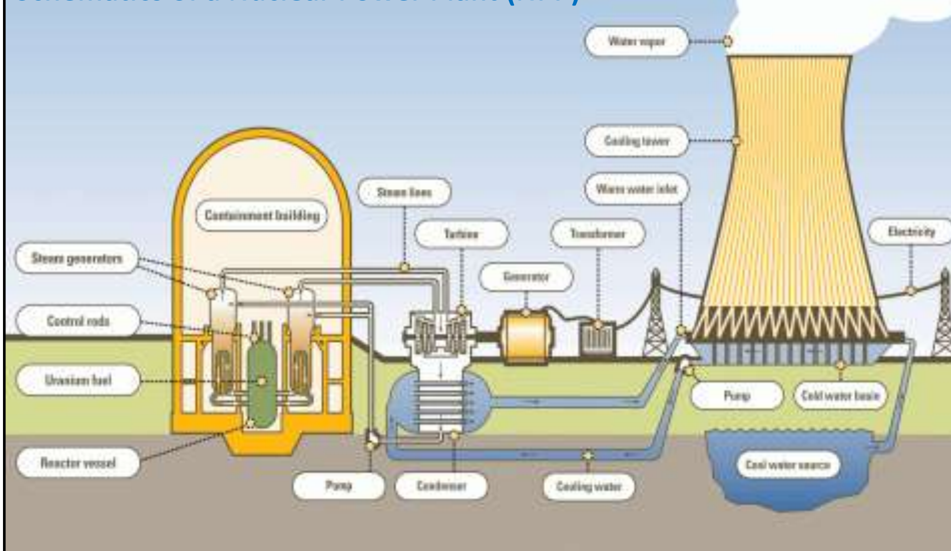
Schematics of a Nuclear Power Plant (NPP)



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How Power Plants Work? Heat Sources!

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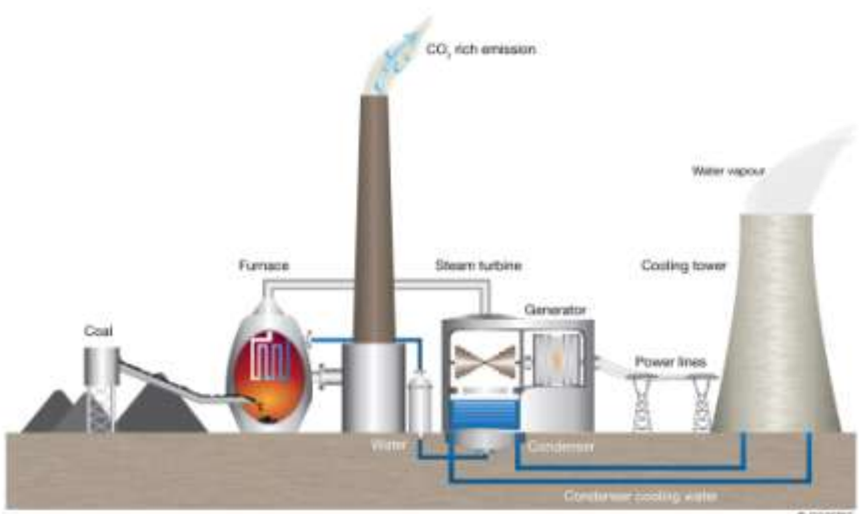
Schematics of a Coal-Fired Power Station



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How Power Plants Work? Heat Sources!

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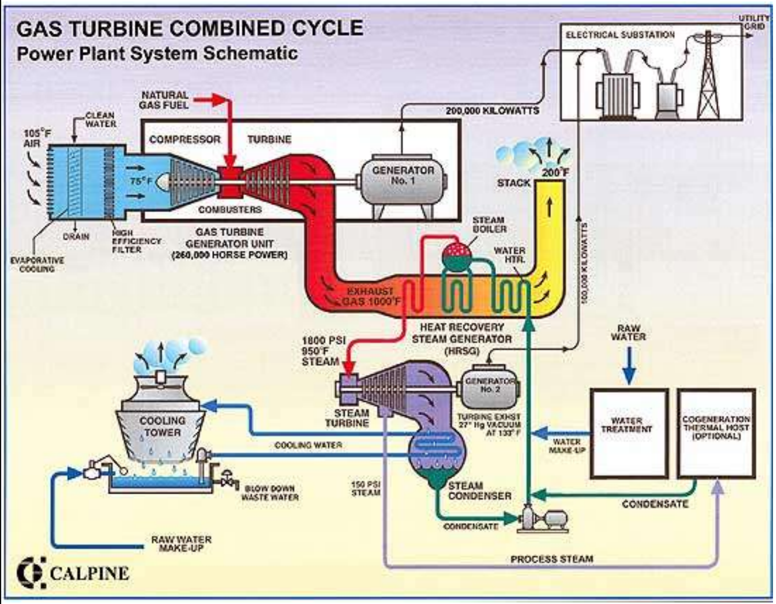

Schematics of a Natural Gas Power Station

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How Power Plants Work? Heat Sources!

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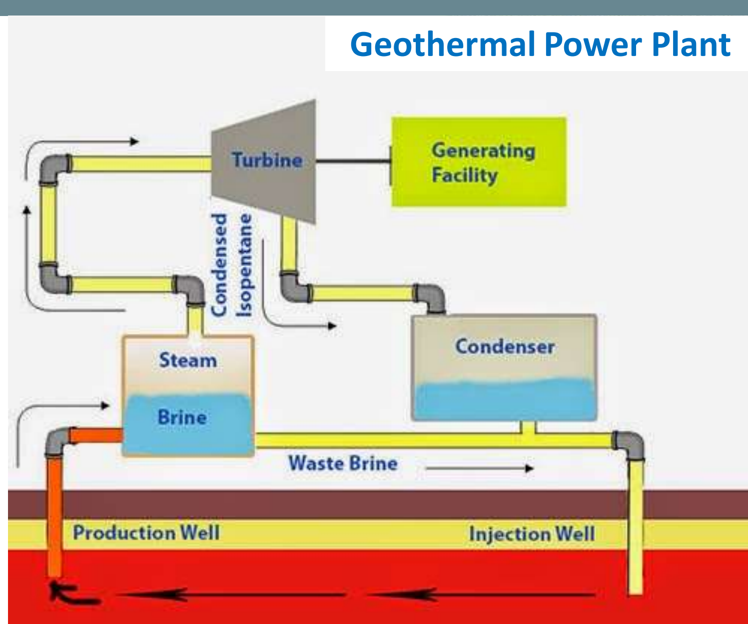

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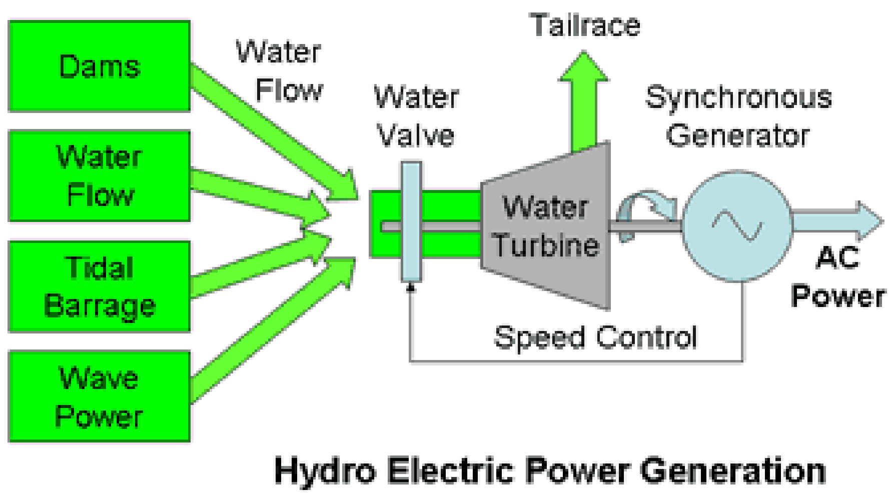
How Power Plants Work? Momentum Sources!



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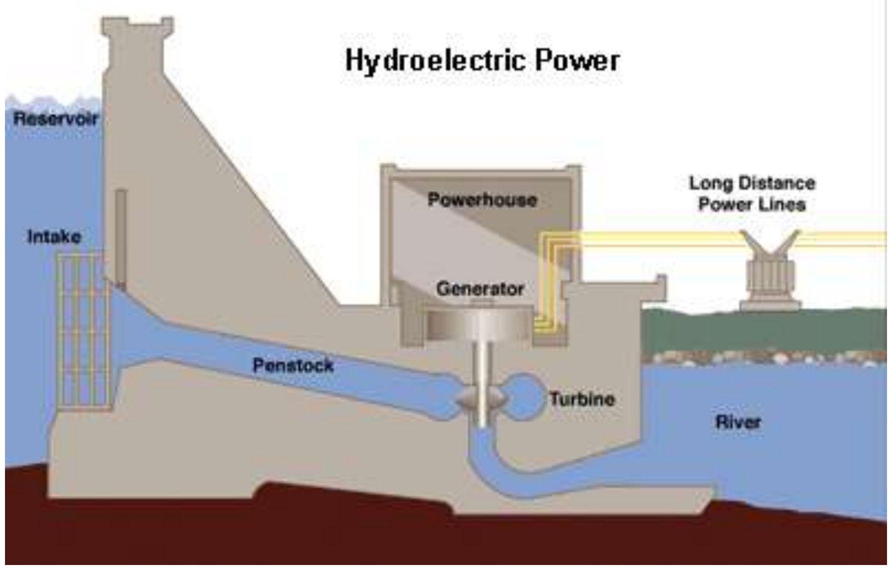

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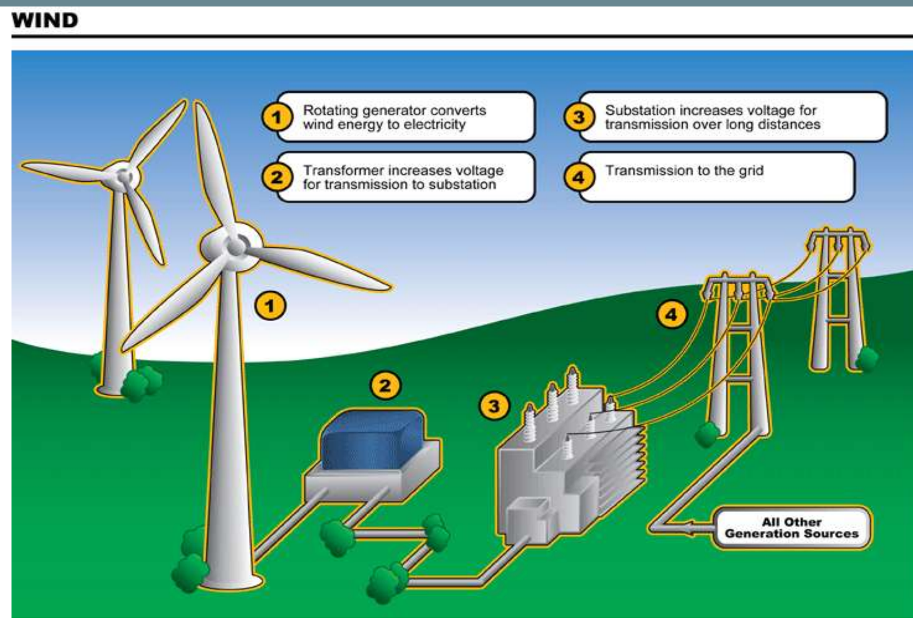

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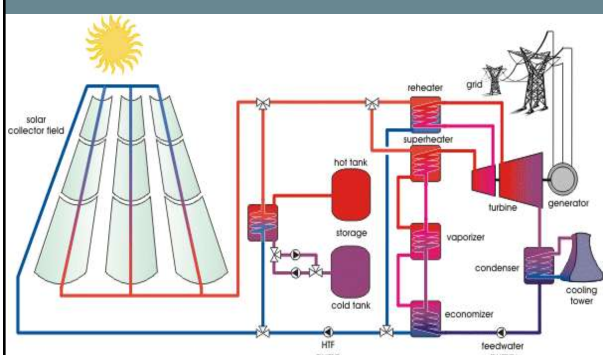
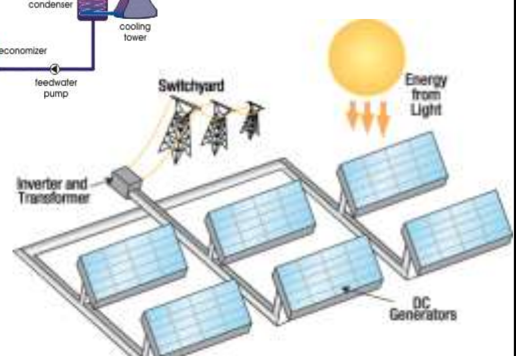
How Power Plants Work? And Solar?



- Heat Source: thermal radiation to boil water or;



- Photovoltaic (solar cells): direct conversion of the electromagnetic radiation from the Sun to electricity.

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How Power Plants Work?

- The vast majority of power plants are based on elements of the following workflow:
  1. Generate heat;
  2. Boil water;
  3. Produced steam is used to turn a (set of) turbine(s);
  4. Turbines are linked with generator to;
  5. Produce electricity.

- We saw that:
  - Fossil fuels and nuclear: 1-5;
  - Hydro and wind: based on momentum transfer + 4-5;
  - Geothermal: undergrounded heated water + 2-5;
  - Solar: (a) solar radiation + 2-5 or,
    (b) photovoltaic cells + 5.

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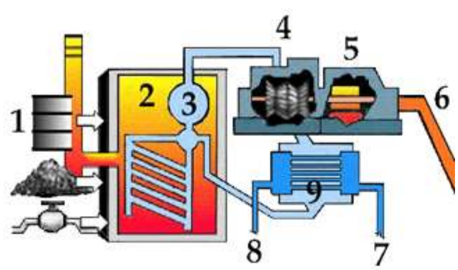
How Power Plants Work? (summary)

1. Energy Source (coal, oil, NG, nuclear, etc) is 'burnt' generating heat in the;
2. Boiler. Heat is transferred into the water-steam cycle (3-4-9-3);
3. Steam (at high temperature and pressure) produced by the water vaporisation is driven towards a;
4. Steam turbine that promotes an isentropic expansion and produces **work**;
5. The **work** is transferred to a generator responsible to produce;
6. Electricity that is linked to the power grid;
7. After the expansion (in the turbine), steam (low temperature and pressure) is driven into the condenser (9), where it is transformed in water and returns to the Boiler (2);



- System 7-8-9 comprises condenser and cooling waste water.

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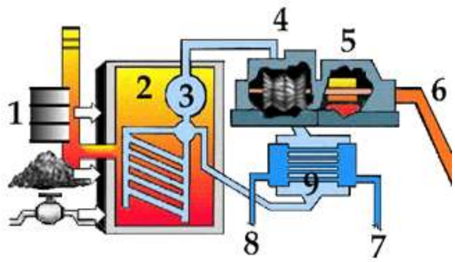

- System 7-8-9 comprises condenser and cooling waste water.

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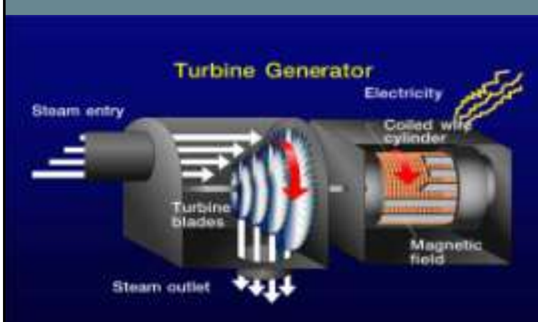
Power Plants: Turbine Generator



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Environmental Impacts of Energy Matrix

FUEL PHASE	Coal	Petroleum	Natural Gas	Nuclear	Hydro	Solar Photovoltaic	Solar Power Tower	Wind	Fusion	Geothermal
Extraction	Mining accident; Lung damage	Drilling-spills (off-shore)	Drilling	Mining accidents; Lung damage	Construction	Mining accidents	--	--	He, Li, H_2 production	--
Refining	Refuse piles	Water pollution	--	Milling tails	--	--	--	--	--	--
Transportation	Collisions	Spills	Pipeline explosions	--	--	--	--	--	--	--
On-Site										
Thermal	High efficiency	High efficiency	High efficiency	Low efficiency	--	High efficiency; Ecosystem change	Ecosystem change	--	--	Low efficiency
Air	Particulates, SO_2, NOx	SO_2, NOx	NOx	Radiation releases	--	--	--	--	--	H_2S
Water	Water treatment chemicals	Water treatment chemicals	Water treatment chemicals	Water treatment chemicals	Destroy prior ecosystems	Water treatment chemicals	Water treatment chemicals	--	Tritium in cooling water	Brine in streams
Aesthetic	Large plant transmission lines	Large plant transmission lines	Large plant transmission lines	Large plant transmission lines	Large plant transmission lines	Poor large areas	Poor large areas	Large areas; Large towers; Noise	Small area	Poor large area
Wastes	Ash; Slag	Ash	--	Spent fuel; Reprocessing waste storage	--	Spent cells	--	Irradiated structural material	--	--
Special Problems	--	--	--	--	--	Construction accidents	--	Bird; Human injuries	Occupational radiation doses	--
Major Accidents	Mining	Oil spills	Pipeline explosions	Reactor cooling and meltdown	Dam failure	Fire	--	--	Tritium release	--

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Source: MITOpenCourseWare

Geothermal Energy: Initial Analysis

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Geothermal Potential in the World Energy Mix

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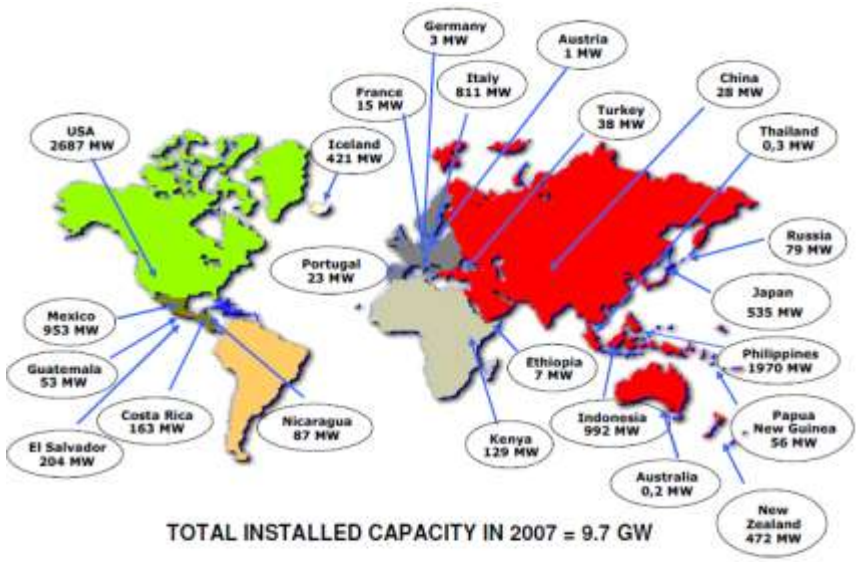

Source: IPCC, 2008

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Geothermal Potential in the World Energy Mix

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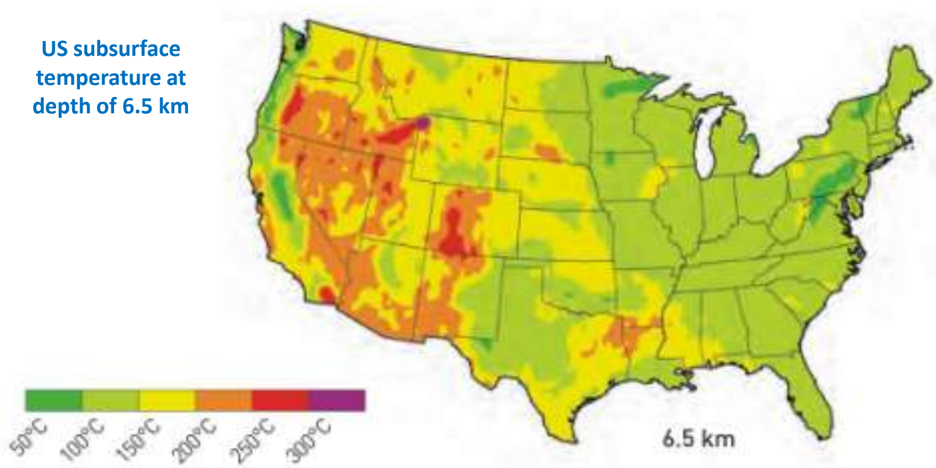
- Geothermal sources of T > 150ºC @ depths of 1500-3000 m: Electricity production;
- Thermal sources 90 ≤ T ≤ 150ºC @ depths below 1000m: Thermal generation.

US subsurface temperature at depth of 6.5 km



Source: MIT (006), The Future of Geothermal Energy

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Geothermal Potential in the World Energy Mix

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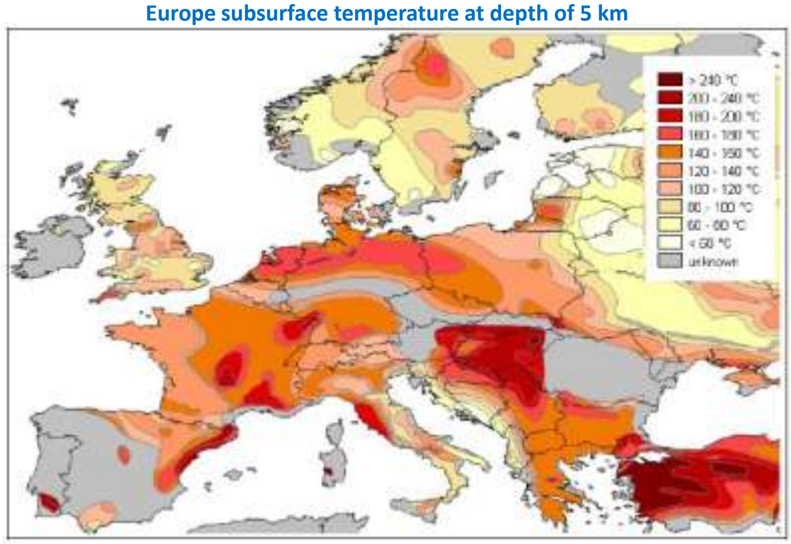
Europe subsurface temperature at depth of 5 km



Source: Trans-Mediterranean Interconnection for Concentrating Solar Power , Final Report (2006)

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Geothermal Potential in the World Energy Mix

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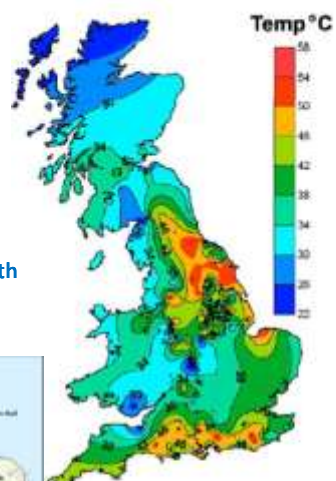
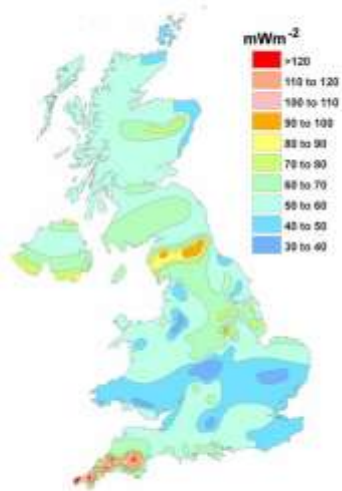
UK subsurface temperature at depth of 1 km





Heat flux based on UK geothermal map

Source: British Geological Survey

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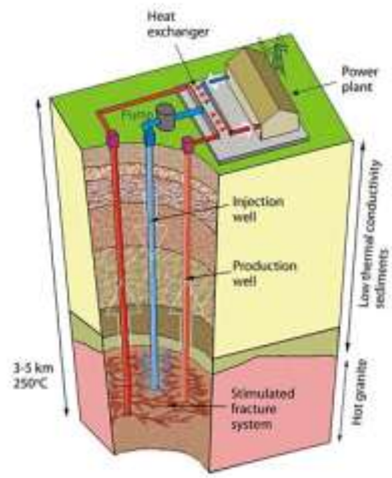
Geothermal Sources

- **Classification:**
  - T > 150ºC (high temperature): electricity production and direct heating;
  - 90 ≤ T ≤ 150ºC (medium temperature): electricity production and direct heating;
  - 30 ≤ T < 90ºC (low temperature): heat pump for heating and air conditioner;
  - T < 30ºC (very low temperature): heat pump for heating and air conditioner.



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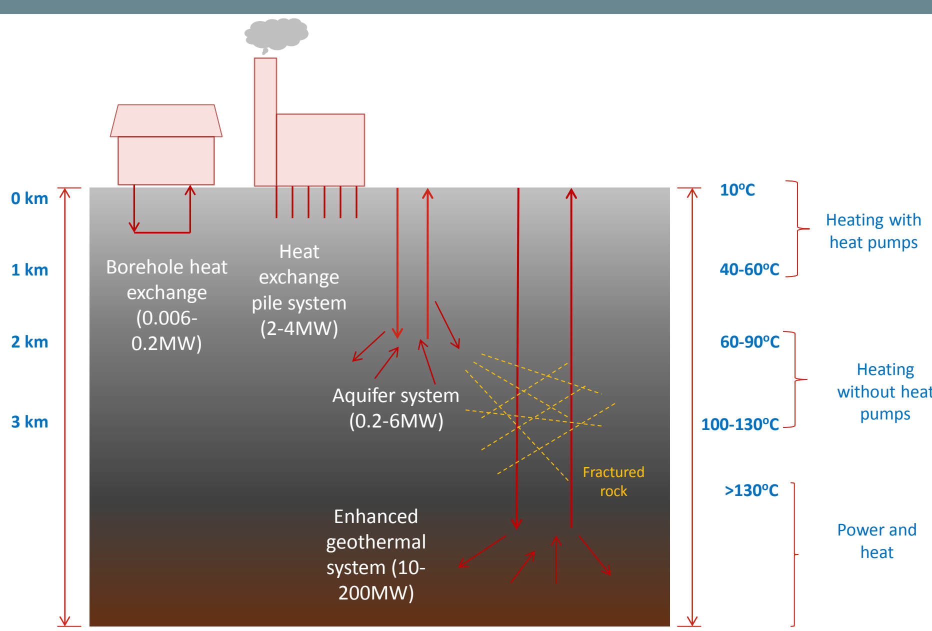
Geothermal Sources



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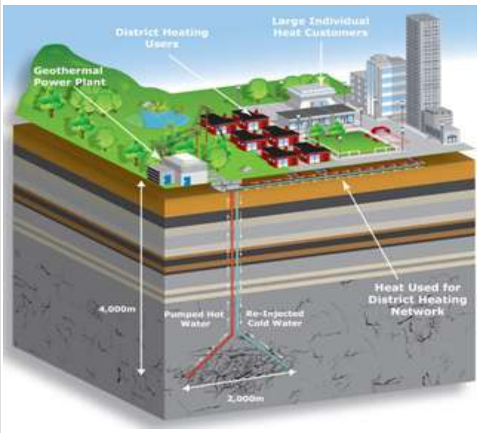
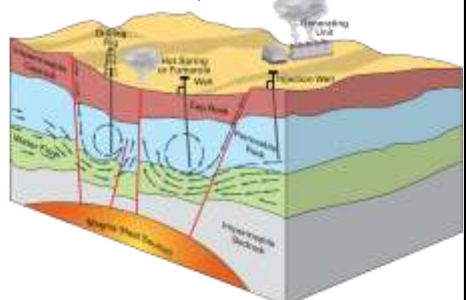
Geothermal Sources: Direct Use



- Hot water can be used for: space heating (52%); bathing & balneology (hot spring, medical etc – 30%); agriculture (greenhouse, fish farming, etc – 12%); industry (4%).

Source: Lund *et al.* (2011) Geothermics 40:159-180.

- The **GS** can be exploited at high temperature with efficiency of 50-70%:
  - Cold water is injected into the permeable rock;
  - Leading to the fracturing of the hot rocks and heat transferring to water;
  - Heated water is diffused and recovered in production well;



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Geothermal Sources: Indirect Use (Power Generation)

- Convert energy stored in hydrothermal fluids to electricity;
- Three main conversion technologies:
  - Dry-steam power plant;
  - Geothermal flash power plant;
  - Binary-cycle power plant
- Choice of technology depends on:
  - Source temperature and reservoir pressure (i.e., depth of the hot fluid reservoir);
  - State of the driving thermal: dry or wet steam, water-steam solution, brine (hot water);
  - Thermo-physical properties of the driving fluid.

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Geothermal Sources: Indirect Use (Power Generation)

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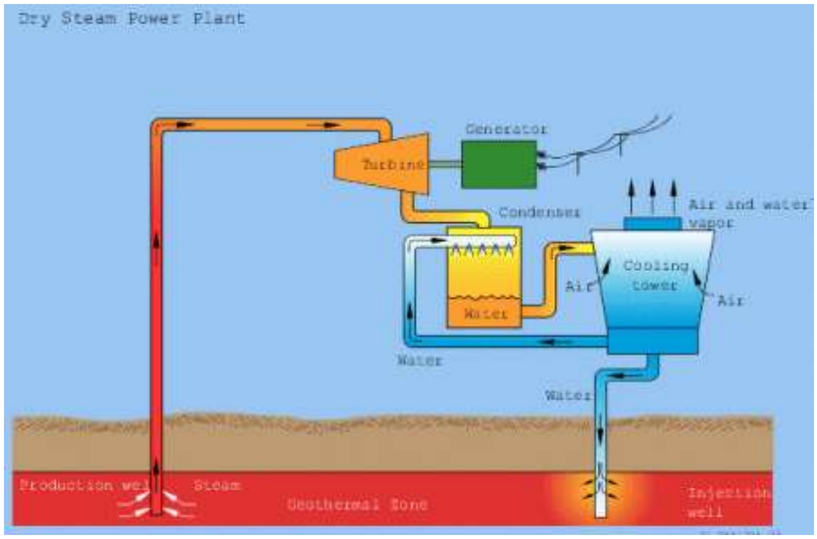
Dry Steam Geothermal Power Plant



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Geothermal Sources: Indirect Use (Power Generation)

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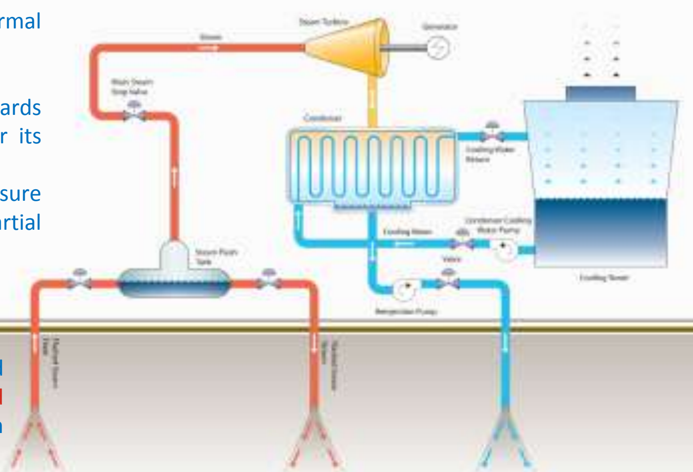
Flashed Steam Geothermal Process Diagram

- Most common geothermal power plant;
- T > 182°C;
- Water is driven upwards through the well under its own pressure;
- As it rises, pressure decreases leading to partial boiling ;



- Liquid (hot) water and steam are separated (flash) and the steam drives the turbine

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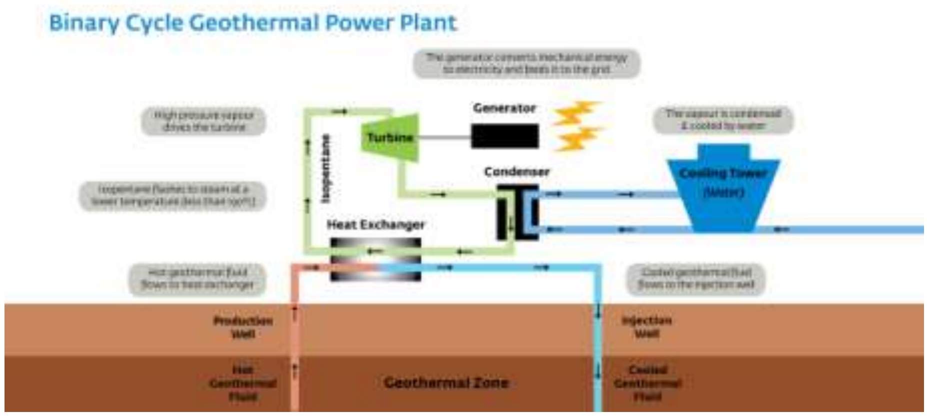
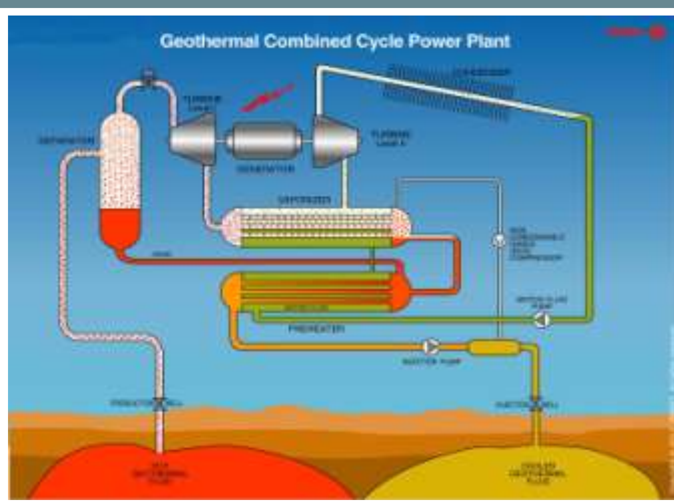
Geothermal Sources: Indirect Use (Power Generation)



- 107≤T ≤ 182°C;
- Hot water is then used to boil the working fluid (often organic compound with low boiling point);
- The vaporized working fluid is used to drive the turbine;
- Thermal water and working fluid are operated in separated cycles with little emissions;

Geothermal Sources: Indirect Use (Power Generation)



- ➢Designed to be used with high and medium temperature sources;
- ➢Combining flash and binary power plant design.

Geothermal Sources: Indirect Use (Power Generation)

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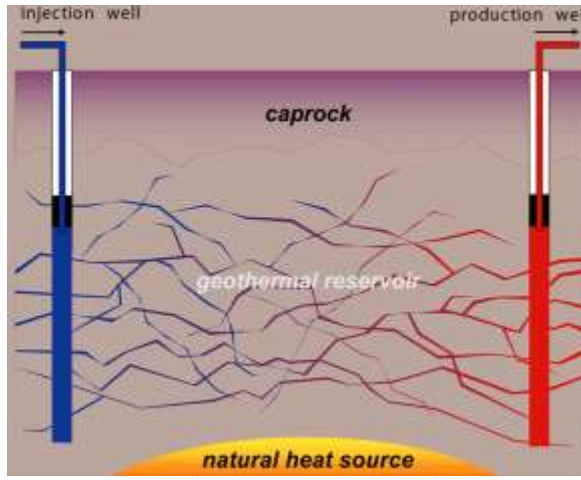
Enhanced Geothermal Systems (EGS)

- Used in deep subsurface with high temperature (150≤T ≤ 200°C);
- Fractures are induced by injection of cold water into deep wells (often with low permeability);
- Heat is transferred from the rocks to the water that is diffused through the fractures and;
- Collected in production wells;
- The hot fluid is then used as part of the previous power technologies.



Source: IPCC (2010) and http://energy.gov/eere/geothermal/how-enhanced-geothermal-system-works

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Geothermal Sources: Indirect Use (Power Generation)

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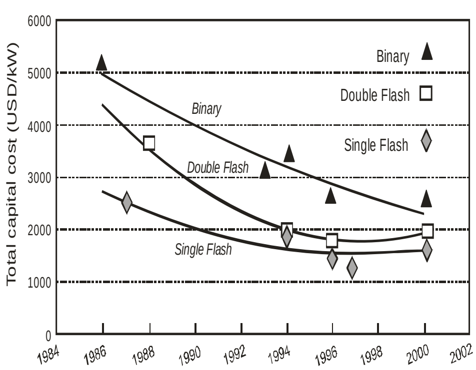
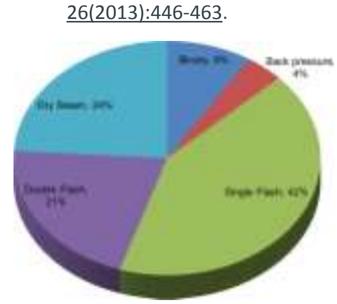


Capital Cost of Geothermal Power Plants in the US

Source: IEA(2006).

Share of different geothermal plant technologies in global electricity production.

Source: Renewable and Sustainable Energy Reviews 26(2013):446-463.



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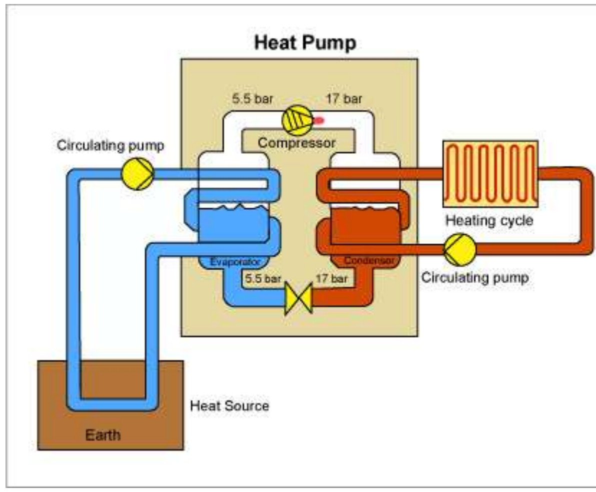
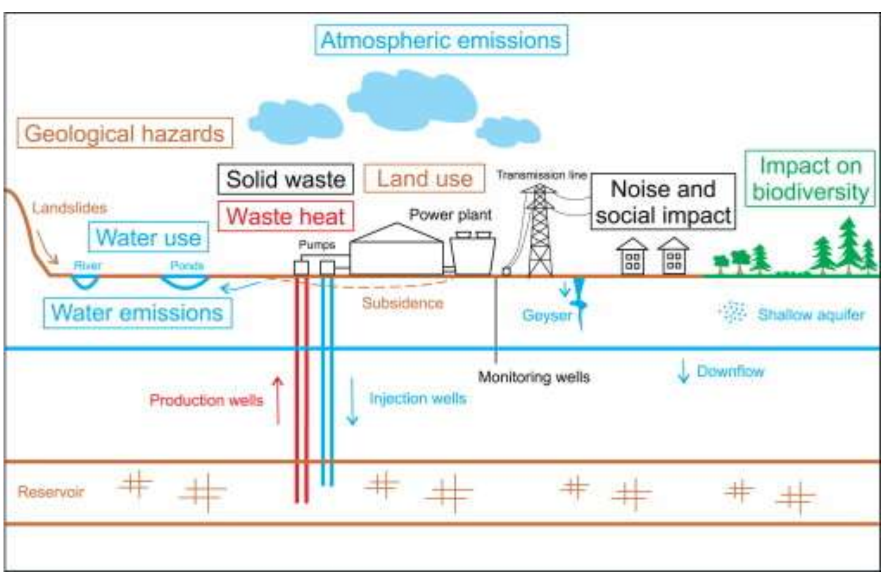
Geothermal Sources: Heat Pump

➢The nearly constant temperature in the soil at low depths (< 4 m) is used by geothermal heat pumps for heating and cooling of houses and industrial facilities;
➢Heat pumps are designed to use this low-grade heat source to keep temperatures of 10°–16°C;
➢This temperature range is enough to keep the environment warmer in the winter and cooler during the summer;
➢It operates two independent cycles.



Environmental Impact



Source: Renewable and Sustainable Energy Reviews 26(2013):446-463.

Environmental Impact

- **Atmospheric Emissions:**
  - NOx: small amounts mainly due to the combustion of H_2S;
  - H_2S (hydrogen sulfide): from volcano gases, petroleum deposits, natural gas and geothermal fluids and need to be captured;
  - SO_2: this compound is not directly released by geothermal power plants, but H_2S can react in the atmosphere and form SO_2;
  - Particulate matter (PM): this involves liquid droplets and particles from smoke, dust and ashes. Water-cooled geothermal power plants do emit small quantities of PM from cooling towers as steam condensates;
  - CO_2 : Geothermal power plants emit small quantities. Some geothermal reservoir fluids contain varying amounts of non-condensable gases, including CO_2.

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Environmental Impact

Plant Type	NO_x (kg/MWh)	SO_2 (kg/MWh)	CO_2 (kg/MWh)	PM
Coal-fired	1.95	4.71	993.82	1.01
Oil-fired	1.81	5.44	758.41	NA
Natural Gas-fired	1.34	0.10	549.75	0.06
Geothermal (flash)	0	0.16	27.21	0
Geothermal (binary & flash/binary)	0	0	0	Traces
Geothermal (geysers dry steam)	Traces	Traces	40.28	Traces

Source: Kagel *et al*. (2007) A Guide to Geothermal Energy and the Environment, http://www.geo-energy.org

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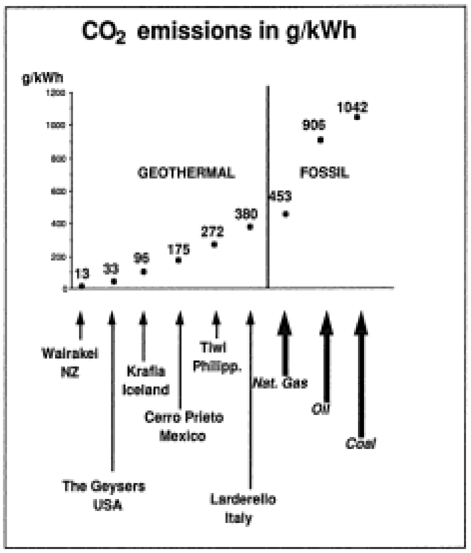
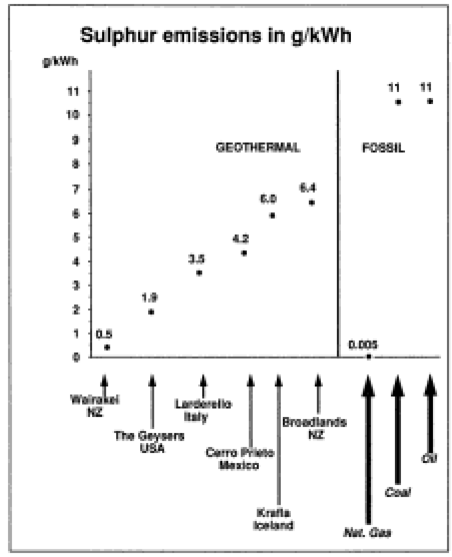
Environmental Impact





Source: Renewable and Sustainable Energy Reviews 6(2002):3-65.

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Environmental Impact

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- **Solid and Liquid Waste:**
  - Arsenic is produced from the subsurface geothermal fluids as part of sludge and scales from the H_2S processing;
  - Waste is produced from drilling activities, as drilling cuttings (mainly bentonites). Mud and cuttings are stored as 'sumps' for disposal.
- **Land Use:** (Tutorial)
  - Properties of small sizes;
  - Subsidence;
  - Induced seismicity;
  - Land slides.
- **Water Quality** (Tutorial)
  - Chemical for water & wastewater treatment;
  - Cool brine.

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Summary

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- Multiple energy sources: fossil-fuel, renewables, nuclear, etc;
- Demand and production of energy mix;
- Thermal and momentum energy sources;
- Current geothermal technologies;
- Environmental impacts;
- Drive for the future.

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Additional Reading

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- BP Statistical Review of World Energy 2013: http://www.bp.com/content/dam/bp/pdf/statistical-review/statistical_review_of_world_energy_2013.pdf
- Annual Energy Outlook 2014 with Projections to 2014 (DoE/EIA-0383): http://www.eia.gov/forecasts/aeo/pdf/0383(2014).pdf
- Annual Energy review 2011 (DoE/EIA-0384): http://www.eia.gov/totalenergy/data/annual/pdf/aer.pdf
- Energy for a Sustainable Future: Reports and Recommendations (2010), The Secretary-General's Advisory Group on Energy and Climate Change (AGECC): http://www.un.org/wcm/webdav/site/climatechange/shared/Documents/AGECC%20summary%20report%5B1%5D.pdf
- The Future of Geothermal Energy: https://www1.eere.energy.gov/geothermal/pdfs/future_geo_energy.pdf
- R. DiPippo (2012) 'Geothermal Power Plants'; Butterworth Heinemann.
- H.K. Gupta (1980) 'Developments in Economic Geology – 12. Geothermal Resources: An Energy Alternative'; Elsevier.
- H.C.H. Armstead (1983) 'Geothermal Energy: Its Past, Present and Future Contribution to the Energy Needs of Man'; E&FN Spon.
- E. Barbier (2002) 'Geothermal Energy Technology and Current Status: An Overview', *Renewable & Sustainable Energy Reviews* 6:3-65.
- S.J. Zarrouk & H. Moon (2014) 'Efficiency of Geothermal Power Plants: A Worldwide Review', *Geothermics* 51:142-153.
- L. Rybach (2003) 'Geothermal Energy: Sustainability and the Environment', *Geothermics* 32:463-470.
- H.N. Pollack, S.J. Hurter, J.R. Johnson (1993) 'Heat Flow from the Earth's Interior: Analysis of the Global Data Set', *Reviews of Geophysics* 31:267-280.

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