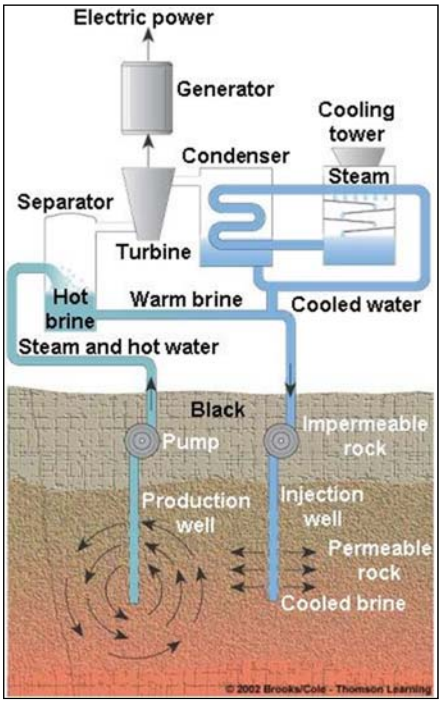
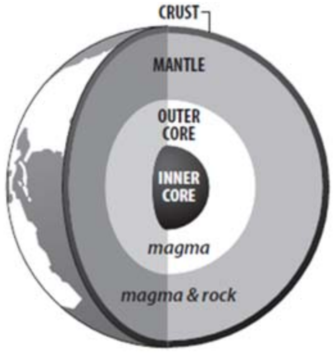


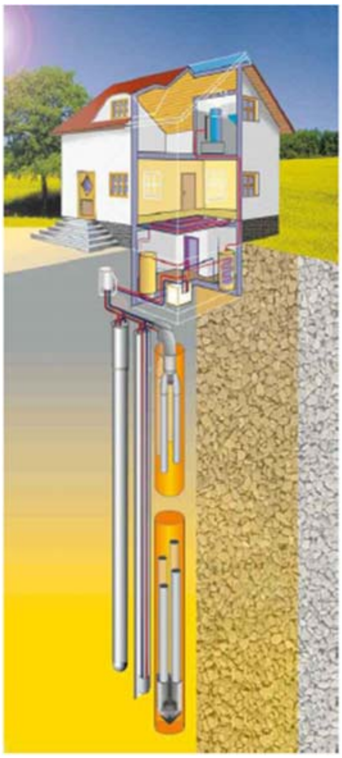
Fuel and Energy

Geothermal Energy



Dr.-Eng. Zayed Al-Hamamre

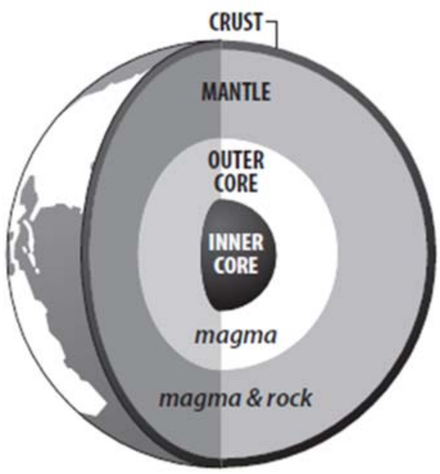
Content



- Introduction
- Heat from the Earth Center
- Geothermal Power Plants
- Environmental Impacts
- Economics consideration

Geothermal Energy

- The word geothermal comes from the Greek words *geo* (earth) and *therme* (heat). Geothermal energy is heat from within the earth.
- Geothermal energy is generated in the earth's **core**, almost 4,000 miles beneath the earth's surface.
- The double-layered core is made up of very hot **magma** (melted rock) surrounding a solid iron center.
- Very high temperatures are continuously produced inside the earth by the slow decay of radioactive particles. This process is natural in all rocks.



- Some visible features of geothermal energy are volcanoes, hot springs, geysers, and fumaroles
- The only way to be sure there is a reservoir is to drill a well and test the temperature deep underground.

Geothermal Site Schematic

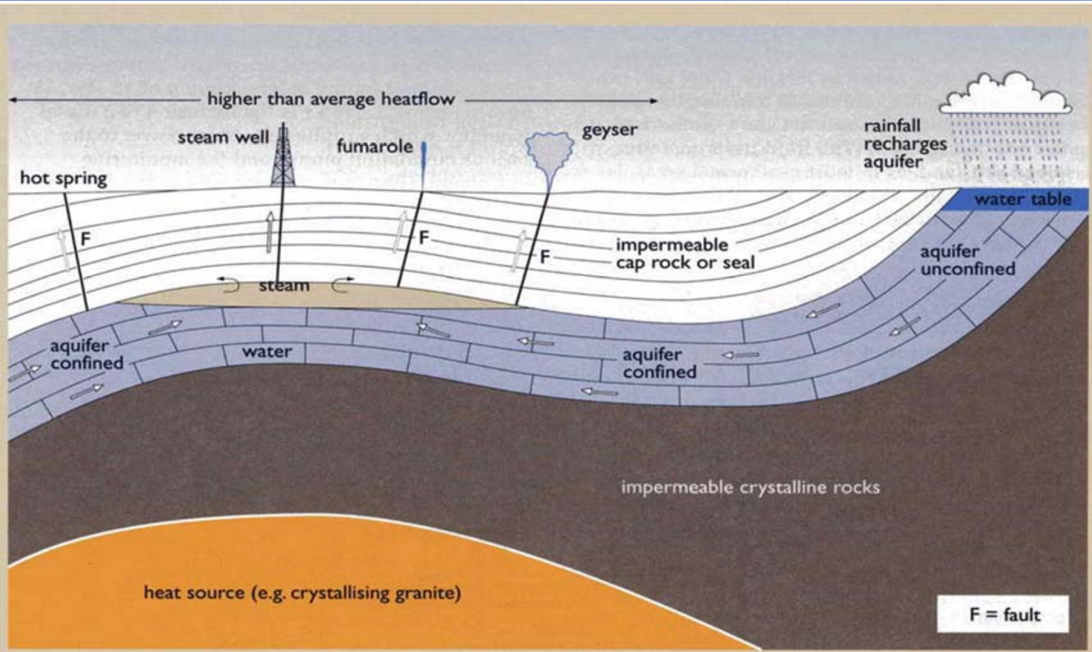
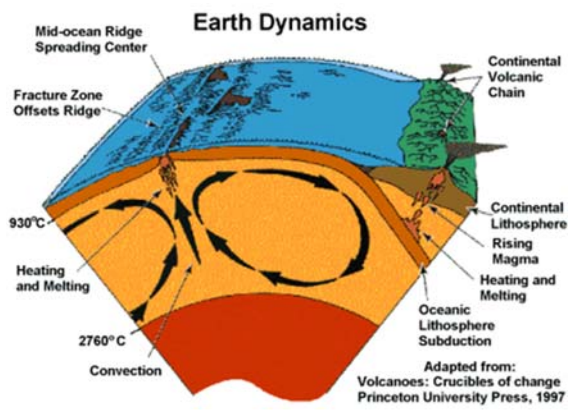


Figure 9.5 Simplified schematic cross-section to show the three essential characteristics of a geothermal site: an aquifer (e.g. fractured limestone with solution cavities); an impermeable cap rock to seal the aquifer (e.g. clays or shales); and a heat source (e.g. crystallising granite). Steam and hot water escape naturally through faults (F) in the cap rock, forming fumaroles (steam only), geysers (hot water and steam), or hot springs (hot water only). The aquifer is unconfined where it is open to the surface in the recharge area, where rainfall infiltrates to keep the aquifer full, as indicated by the water table just below the surface. The aquifer is confined where it is beneath the cap rock. Impermeable crystalline rocks prevent downward loss of water from the aquifer

Heat from the Earth's Center

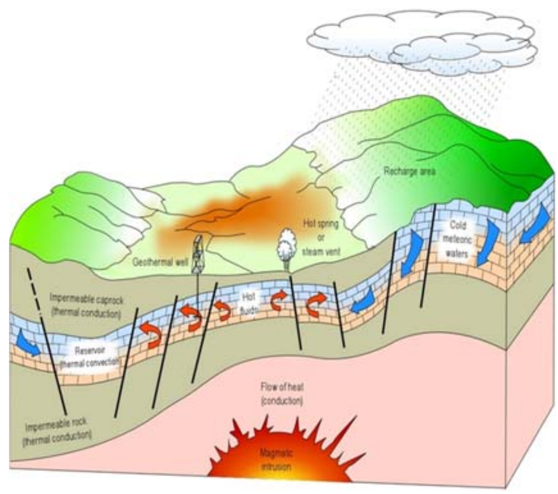
- The gradual radioactive decay of elements within the earth maintains the earth's core at temperatures in excess of 5000°C.
- Heat energy continuously flows from this hot core by means of conductive heat flow and convective flows of molten mantle beneath the crust.
- The result is that there is a mean heat flux at the earth's surface of around 16 kilowatts of heat energy per square kilometer which is dissipated to the atmosphere and space.



- This heat flux is not uniformly distributed over the earth's surface but tends to be strongest along tectonic plate boundaries where volcanic activity transports high temperature material to near the surface.
- Only a small fraction of the molten rock feeding volcanoes actually reaches the surface. Most is left at depths of 5-20 km beneath the surface, where it releases heat that can drive hydrological convection that forms high temperature geothermal systems at shallower depths of 500-3000m

Heat from the Earth's Center

- The heat from the earth's core continuously flows outward. It transfers (conducts) to the surrounding layer of rock, the *mantle*.
- When temperatures and pressures become high enough, some mantle rock melts, becoming *magma*.
- Then, because it is lighter (less dense) than the surrounding rock, the magma rises (convects), moving slowly up toward the earth's crust, carrying the heat from below



- Deep underground, the rocks and water absorb the heat from the magma.
- The heated, underground water can be pump to the surface through a well
- Geothermal energy is called a **renewable** energy source because the water is replenished by rainfall and the heat is continuously produced deep within the earth.

Sources for Heat Flow

- The release of heat due to the cooling of the Earth and the heat produced by radioactivity appear to be primarily responsible for the heat flow observed at the surface of the Earth and the temperature distribution within it

$$^{238}U = {}^{206}Pb + 8\,{}^{4}He + 51.6\ MeV$$
$$^{235}U = {}^{207}Pb + 7\,{}^{4}He + 46.2\ MeV$$
$$^{232}Th = {}^{208}Pb + 6\,{}^{4}He + 42.6\ MeV$$

- Heat production of a rock is the total heat produced by the radioactive isotopes of U, Th, and K.
- It is defined as the quantity of heat produced by radioactivity in unit volume of the rock per unit time, and is expressed in $\mu W\, m^{-3}$

$$\text{Heat production } (\mu W\, m^{-3}) = 10^{-5}\, \rho(3.48 C_K + 9.52 C_U + 2.56 C_{Th}),$$

Sources for Heat Flow

where C_U and C_{Th} are uranium and thorium contents expressed in ppm, C_K the potassium content expressed in weight percent, and ρ the density of the rock expressed in $kg\, m^{-3}$.

Major radioactive isotopes found in rocks, their half-lives, and heat production

Isotope	Half-life (yr)	Heat production ($J\, kg^{-1}\, yr^{-1}$)
^{238}U	4.50×10^9	2.97×10^3
^{235}U	0.71×10^9	18.01×10^3
^{232}Th	13.9×10^9	0.83×10^3
^{40}K	1.30×10^9	0.92×10^3

Material	K	U	Th
Heat production (W/kg of element)	3.5×10^{-9}	96.7×10^{-6}	26.3×10^{-6}

Sources for Heat Flow

For example, a rock formation with density $2670\,kg\,m^{-3}$ and containing the average concentrations (2 ppm uranium, 8 ppm thorium, and 2% potassium) would produce

$1.24\,\mu W\,m^{-3}$ of heat.

Heat Production from Radioactivity, in J/kg-s

Material	K	U	Th	Total
Upper continental crust	9.29×10^{-11}	2.45×10^{-10}	2.77×10^{-10}	6.16×10^{-10}
Average continental crust	4.38×10^{-11}	9.82×10^{-11}	6.63×10^{-11}	2.07×10^{-10}
Oceanic crust	1.46×10^{-11}	4.91×10^{-11}	2.39×10^{-11}	8.76×10^{-11}
Mantle	3.98×10^{-14}	4.91×10^{-13}	2.65×10^{-13}	7.96×10^{-13}
Bulk Earth	6.90×10^{-13}	1.96×10^{-12}	1.95×10^{-12}	4.60×10^{-12}

Heat Flow

Conduction

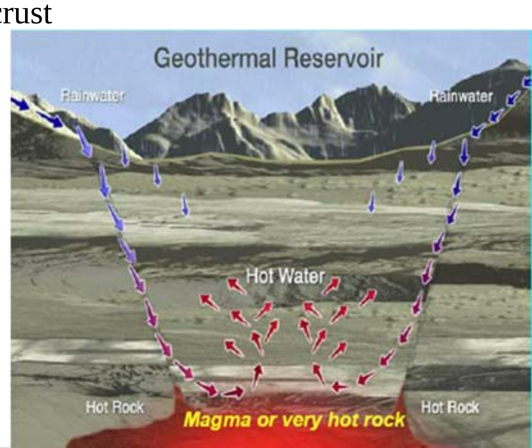
- Heat from the Earth's interior flows outward.
- It is transferred to the outer layer of rock or the crust.

Rainwater

- Rainwater seeping downward through pores and crevices in the crust to depths of a mile or more is heated.
- The heated water may be stored at depth in geothermal reservoirs, or the hot water may flow upward out the reservoirs to the surface as hot springs, or boil near the surface to create geysers, fumeroles, and mudpots.

Convection

- In some regions, the mantle beneath the crust may be hot enough to partly melt and create magma.
- Magma rising upward out of the mantle can bring intentse shallow heat into the crust



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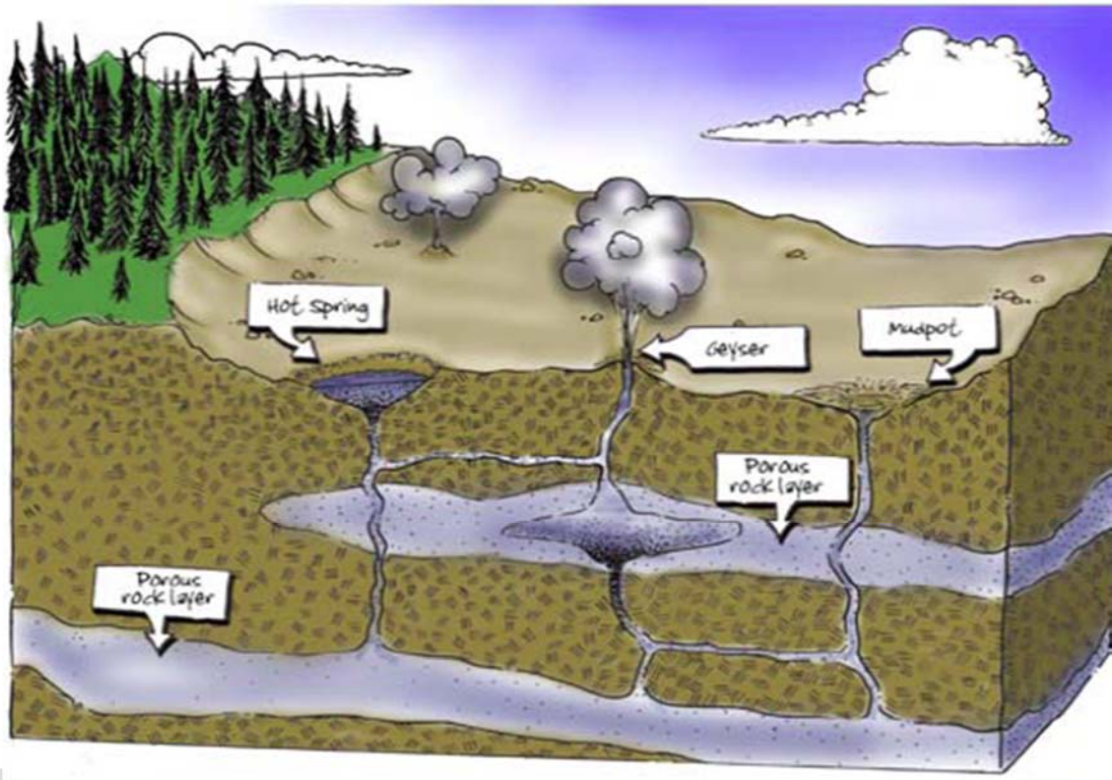
Heat Flow



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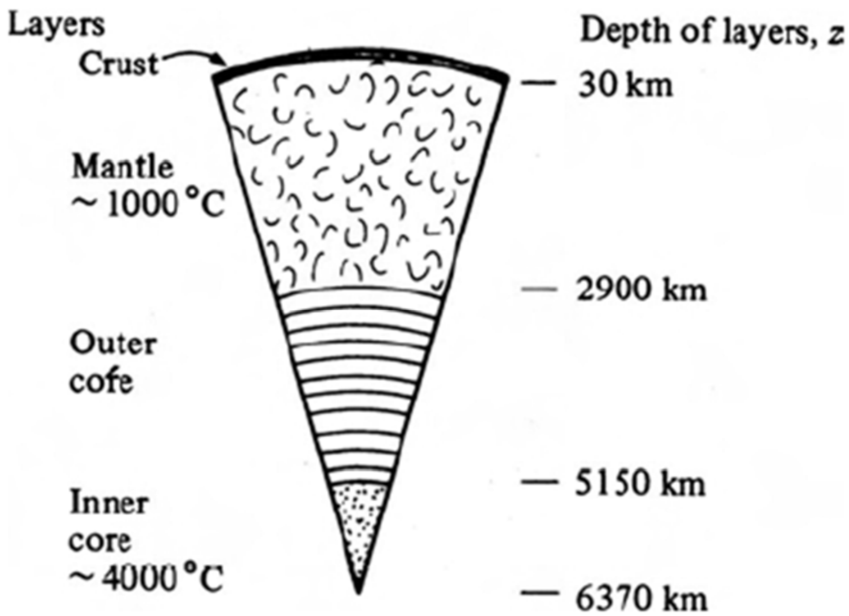
Earth's Temperatures



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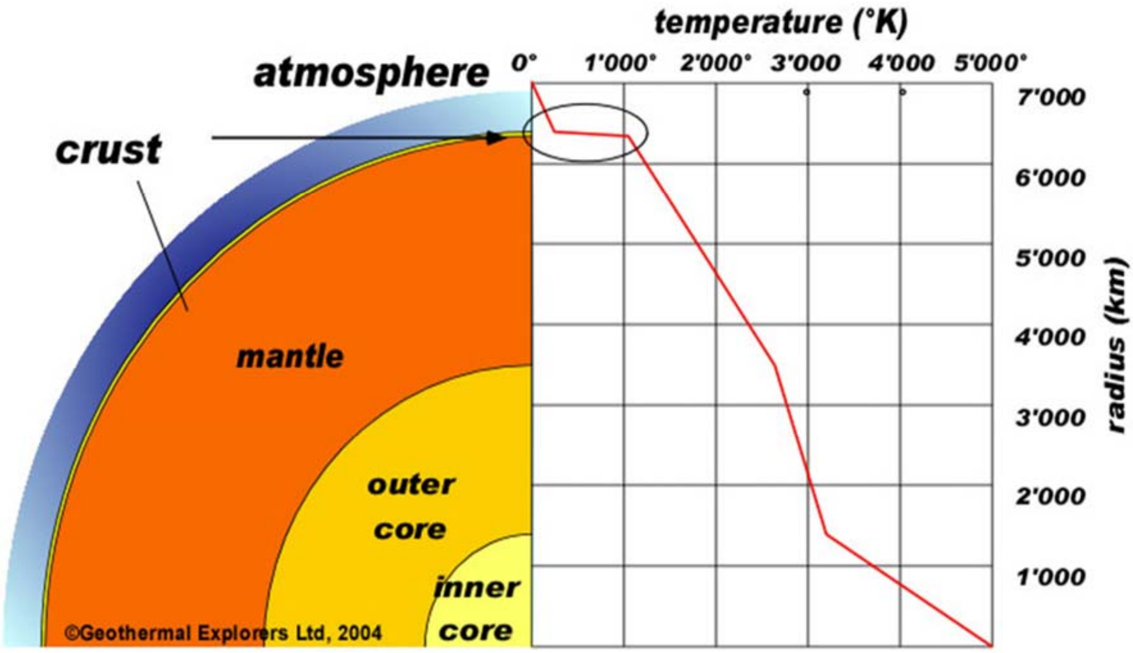
Earth Temperature Gradient



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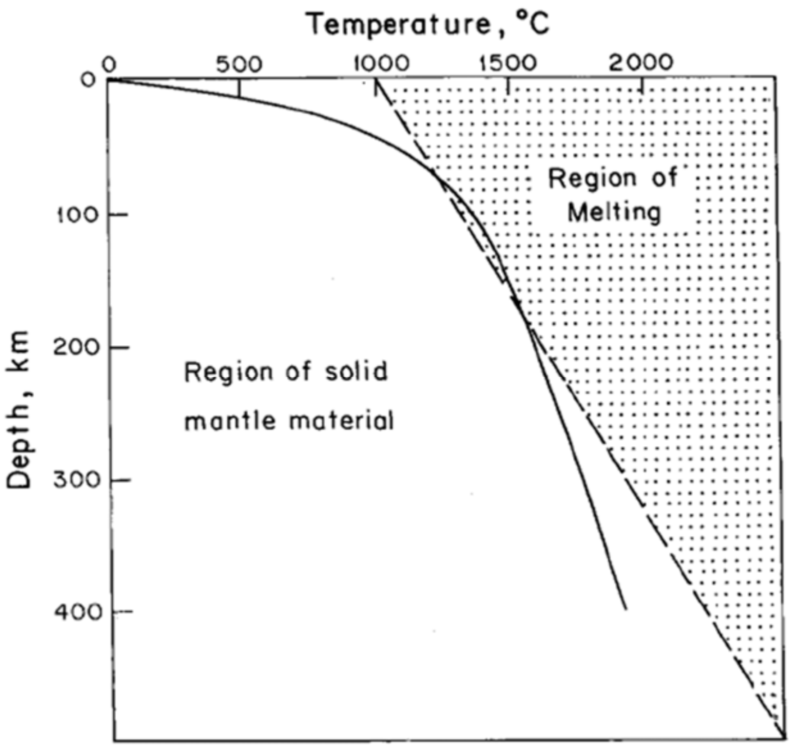
Earth Temperature Gradient



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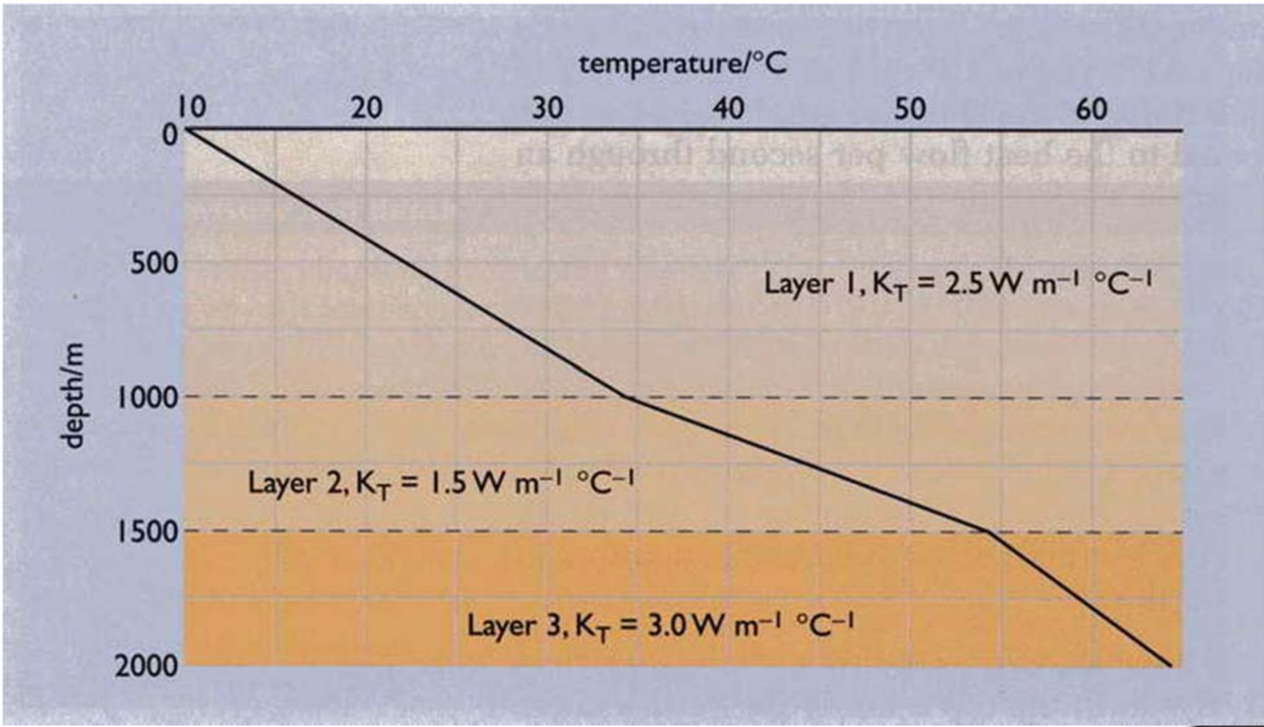
Temperature Gradients



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Geysers

- A **geyser** is a type of hot spring that erupts periodically, ejecting a column of hot water and steam into the air.

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Hot Springs

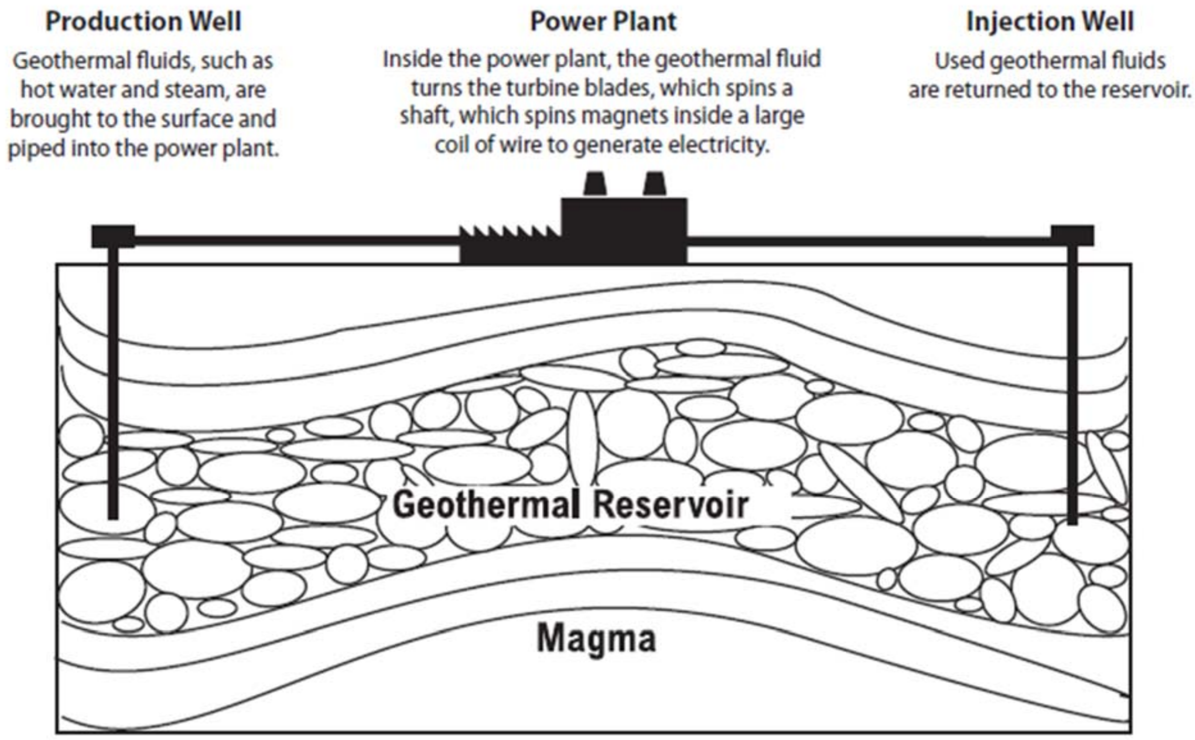
Fumaroles

Clay Diablo Fumarole (CA)

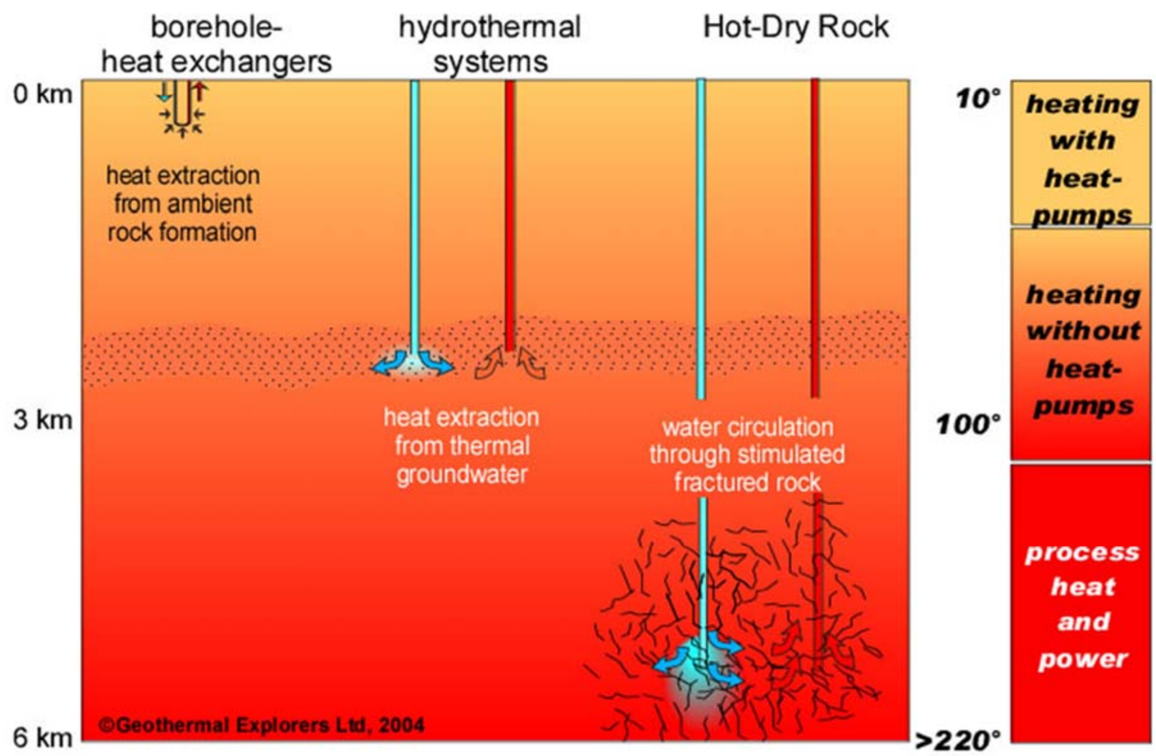
White Island Fumarole

New Zealand

Geothermal Power Plants

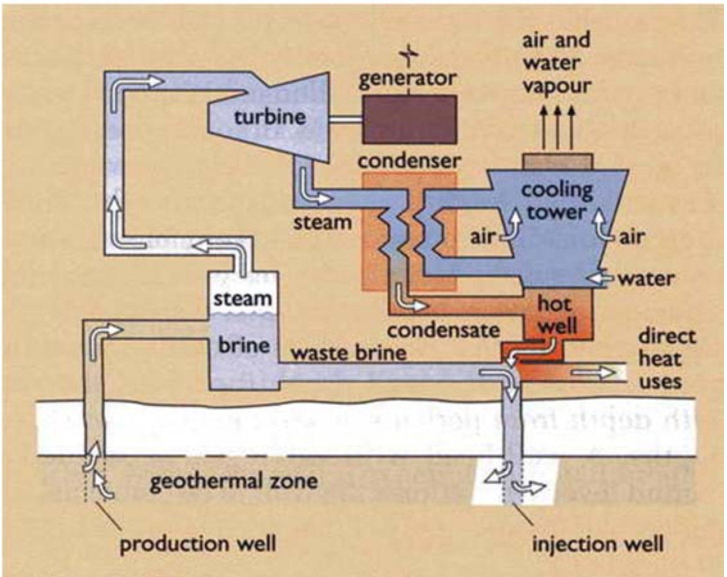


Methods of Heat Extraction



Single Flash Power Plant

- Steam with water extracted from ground
- Pressure of mixture drops at surface and more water “flashes” to steam
- The steam is separated in a surface vessel (steam separator)
- Steam drives a turbine
- Turbine drives an electric generator
- Generate between 5 and 100 MW
- Use 6 to 9 tonnes of steam per hour



(b) single flash steam power plant

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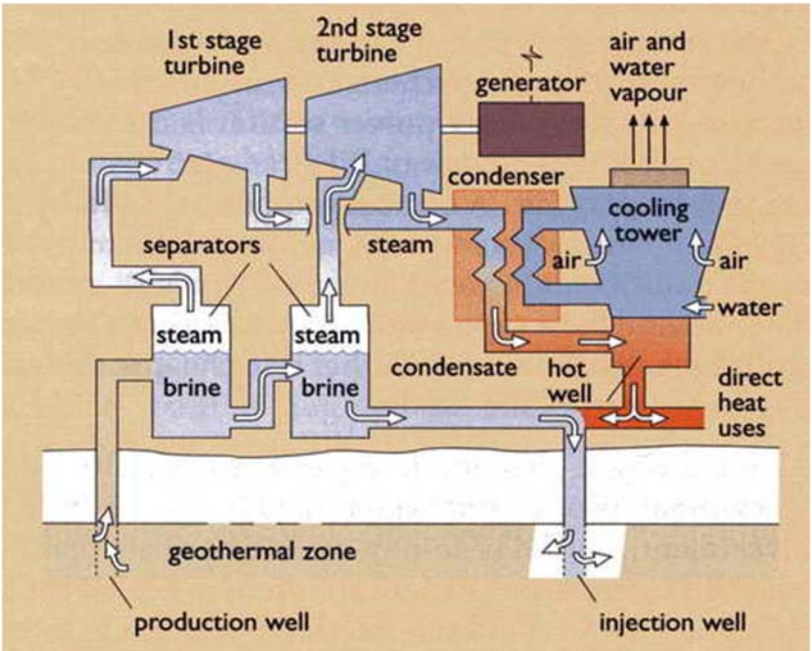
Double Flash Power Plant

- Similar to single flash operation
- Unflashed liquid flows to low-pressure tank – flashes to steam
- Steam drives a second-stage turbine
  - Also uses exhaust from first turbine
- Increases output 20-25% for 5% increase in plant costs



(d) double flash power plant

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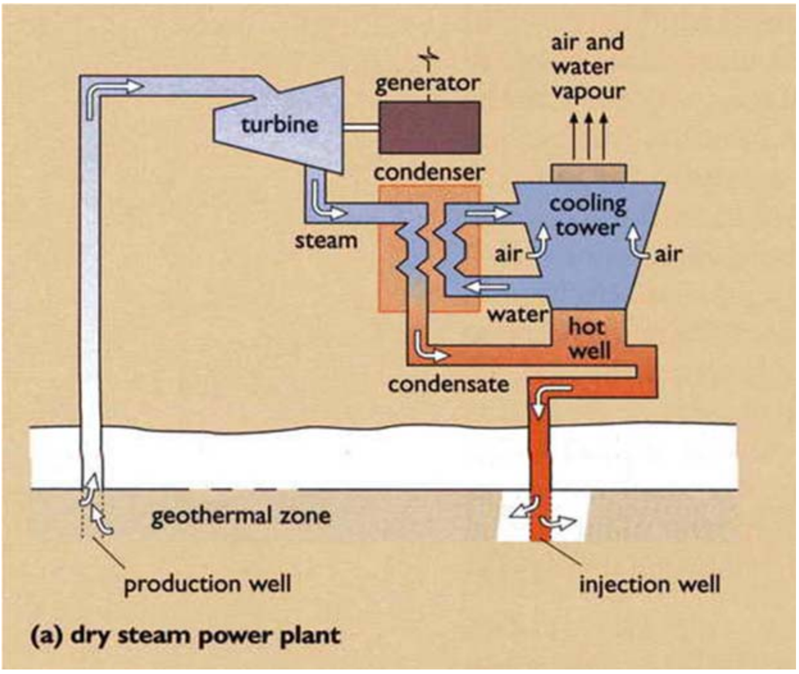
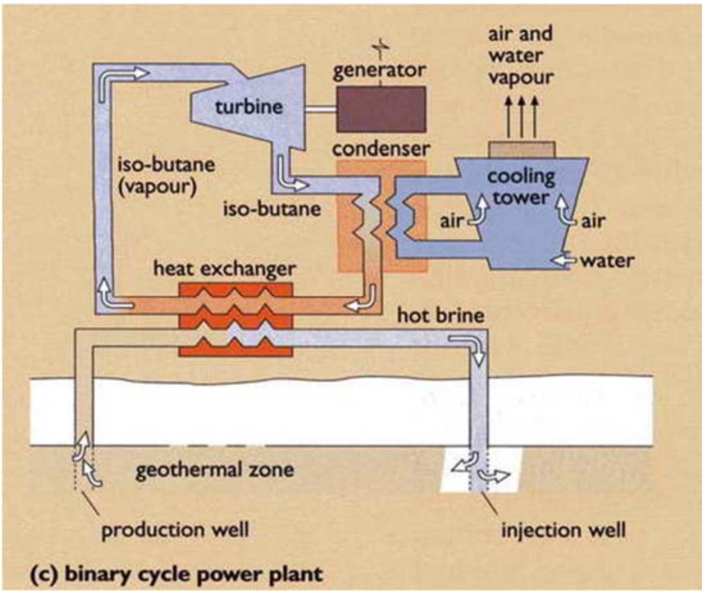
Dry Steam Plant

- Steam directly extracted from natural reservoir
  - 180-225 ºC (356-437 ºF)
  - 4-8 MPa (580-1160 psi)
  - 200+ km/hr (100+ mph)
- Steam is used to drive a turbo-generator
- Steam is condensed and pumped back into the ground
- Can achieve 1 kWh per 6.5 kg of steam
  - A 55 MW plant requires 100 kg/s of steam



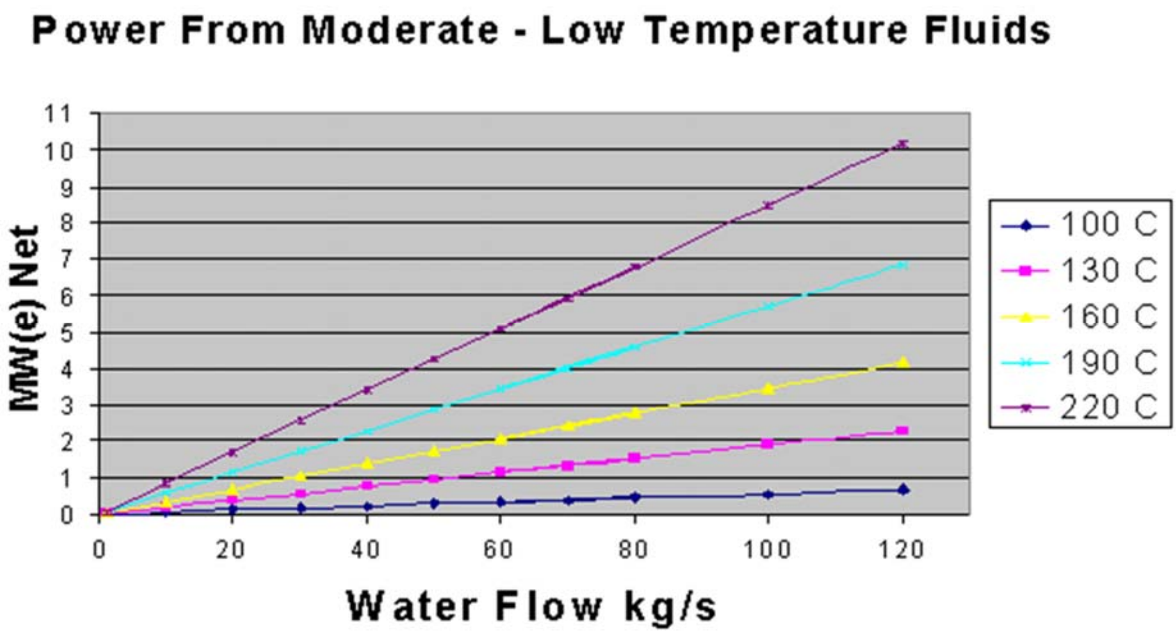
Binary Power Plant

- In the binary process, the geothermal water heats another liquid, such as isobutane or iso-butane, iso-pentane, that boils at a lower temperature than water.
- The two liquids are kept completely separate through the use of a heat exchanger used to transfer the heat energy from the geothermal water to the .working-fluid."
- The secondary fluid vaporizes into gaseous vapor and (like steam) the force of the expanding vapor turns the turbines that power the generators



- Low temps – 100º and 150ºC
- Typically 7 to 12 % efficient
- 0.1 – 40 MW units common

Binary Plant Power Output



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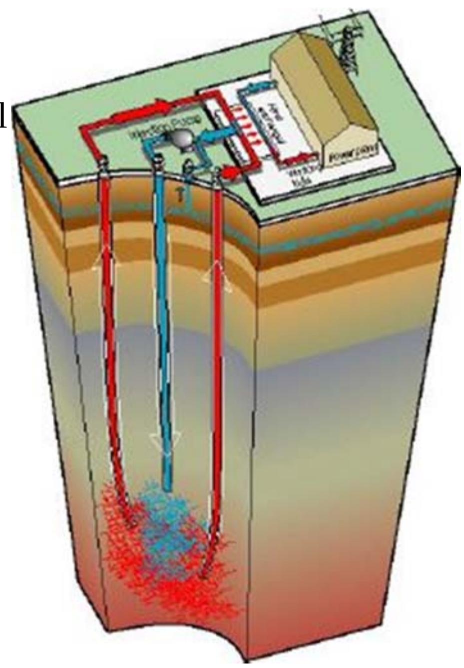
Hot Dry Rock Technology



- Wells drilled 3-6 km into crust
  - Hot crystalline rock formations
- Pressurized cold water is sent down the injection well where the hot rocks heat the water up
- Water flows through natural fissures picking up heat
- Hot water/steam returns to surface
- Steam used to generate power or passed near a liquid with a lower boiling temperature, such as an organic liquid like butane. The ensuing steam turns the turbines
- 1 km^3 of hot rock has the energy content of 70,000 tonnes of coal
  - If cooled by 1 ºC
- Between 19-138 GW power available at existing hydrothermal sites
  - Using enhanced technology

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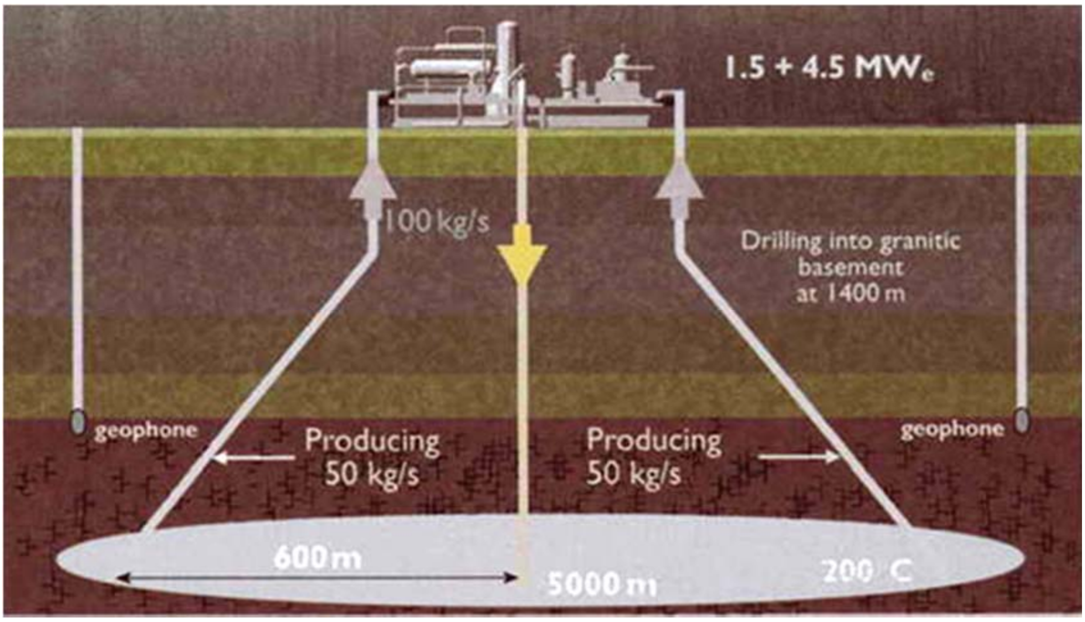
Hot Dry Rock Technology



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2-Well HDR System Parameters

Table 9.6 Target parameters for a 2-well HDR system

Flow rate	75–100 kg s^{-1}
Effective heat exchange area	$> 2 \times 10^6$ m^2
Accessible rock volume	$> 2 \times 10^8$ m^3
Impedance *	0.1 MPa l^{-1} s^{-1}
Water losses	< 10%

* Note: strictly, impedance is not a constant, but varies with flow rate (pressure). The specified figure is the resistance to flow at the operating rate

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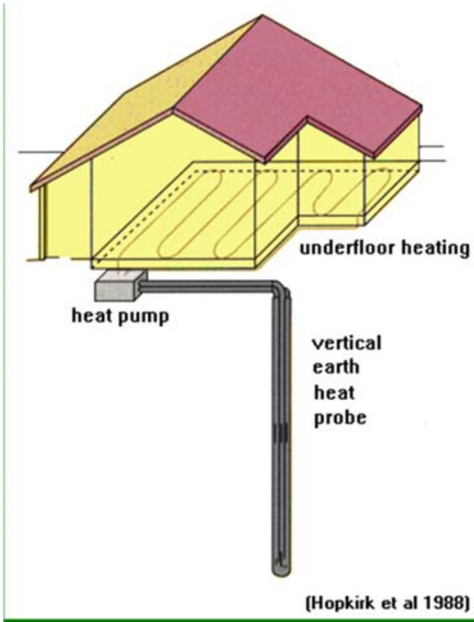
Direct Use Technologies

- Geothermal heat is used directly rather than for power generation
- Extract heat from low temperature geothermal resources
  - < 150 °C or 300 °F.
- Applications sited near source (<10 km)
- Direct Sources function by sending water down a well to be heated by the Earth's warmth.
- Then a heat pump is used to take the heat from the underground water to the substance that heats the house.
- Then after the water it is cooled is injected back into the Earth.



Schema of a U tube system installed in a small diameter well

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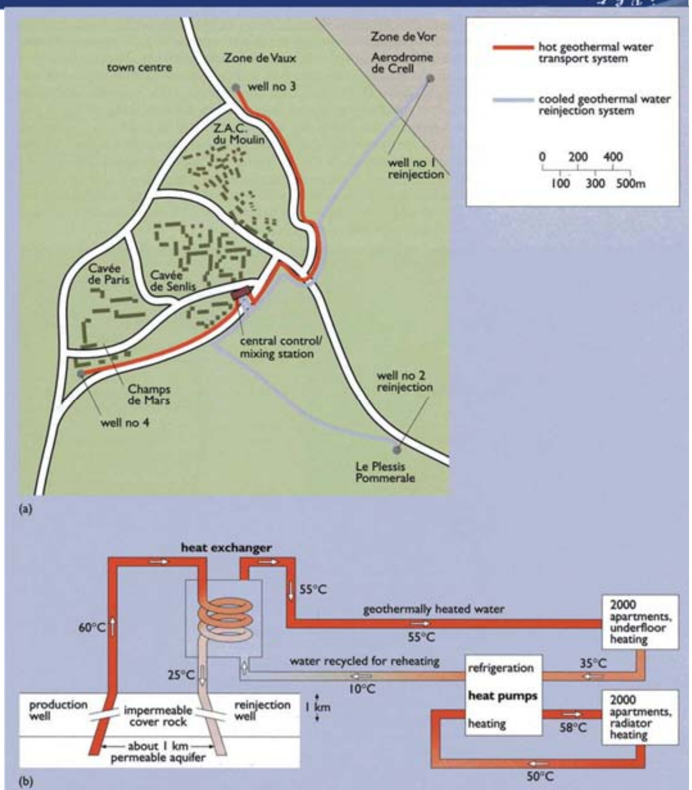
Direct Use Technologies

Ground Heat Collectors

- This system uses horizontal loops filled with circulating water at a depth of 80 to 160 cm underground.

Borehole Heat Exchange

- This type uses one or two underground vertical loops that extend 150 meters below the surface.



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Direct Use Technologies

Direct uses of geothermal energy is appropriate for sources below 150^{o}C

- space heating
- air conditioning
- industrial processes
- drying
- Greenhouses
- Aguaculture
- hot water
- resorts and pools
- melting snow

Crop dehydration plant in Nevada.

A fish farm in Colorado

Greenhouse in Colorado

Geothermal Plants and Cooling Systems

- A cooling system is essential for the operation of any modern geothermal power plant.
- Cooling towers prevent turbines from overheating and prolong facility life.
- Most power plants, including most geothermal plants, use water cooling systems

- A combination of flash and binary technology, known as the **flash/binary combined cycle**, has been used effectively to take advantage of the benefits of both technologies.
- In this type of plant, the flashed steam is first converted to electricity with a backpressure steam turbine, and the low-pressure steam exiting the backpressure turbine is condensed in a binary system.
- This allows for the effective use of air cooling towers with flash applications and takes advantage of the binary process.
- The flash/binary system has a higher efficiency where the well-field produces high pressure steam, while the elimination of vacuum pumping of noncondensable gases allows for 100 percent injection.

Technology vs. Temperature

Reservoir Temperature	Reservoir Fluid	Common Use	Technology commonly chosen
High Temperature >220°C (>430°F).	Water or Steam	Power Generation Direct Use	• Flash Steam • Combined (Flash and Binary) Cycle • Direct Fluid Use • Heat Exchangers • Heat Pumps
Intermediate Temperature 100-220°C (212 - 390°F).	Water	Power Generation Direct Use	• Binary Cycle • Direct Fluid Use • Heat Exchangers • Heat Pumps
Low Temperature 50-150°C (120-300°F).	Water	Direct Use	• Direct Fluid Use • Heat Exchangers

Temperature-Based Classification of Geothermal Energy

Resource Temperature	Best Applications For Geothermal Heat*
Surface Temperature (40°F to 80°F)	Geothermal HVAC systems for homes and buildings
Low Temperature (70°F to 165°F)	Direct Use: agriculture and greenhouses, aquaculture (fish farming), mineral water spas and bath facilities, district water heating, soil warming, fruit & vegetable drying, concrete curing, food processing
Moderate Temperature (165°F to 300°F)	Binary fluid generators for electrical production; Direct Use: absorption chillers, fabric dyeing, pulp and paper processing, lumber and cement drying, sugar evaporation
High Temperature (>300°F)	Electricity production, minerals recovery, hydrogen production, ethanol and biofuels production

Benefits

- Geothermal energy is a geologically sourced renewable resource that is basically constant in a human timeframe.
- Geothermal energy is versatile. It can cool and heat through Geothermal systems, it can produce direct heat for various industries, and it can generate electrical power in Texas.
- Geothermal energy is considered pollution free and does not contribute to greenhouse heating. Some of the newest binary power plants have no emissions while others emit only 0.3 lb of carbon (CO_2) per MWh of electricity generated.
- Geothermal power plants have a high capacity factor, running 98% of the time with routine maintenance constituting the primary downtime. They supply base load electrical power.
- Although the Geothermal system infrastructure costs are slightly higher the payback is better in the long run. They have lower operating costs and are far more energy efficient than conventional systems, and the money saved on energy bills usually covers the initial investment in two to ten years.

Benefits

- Geothermal HVAC systems typically have lower maintenance than conventional systems, as all of the equipment is installed inside the building or underground. Unoccupied parts of a building can easily be shut down due to the more modular nature of this system.

Technology	Capacity Factor, Percentage Range
Geothermal	89 – 97
Biomass*	80
Wind	26 – 40
Solar**	22.5 – 32.2

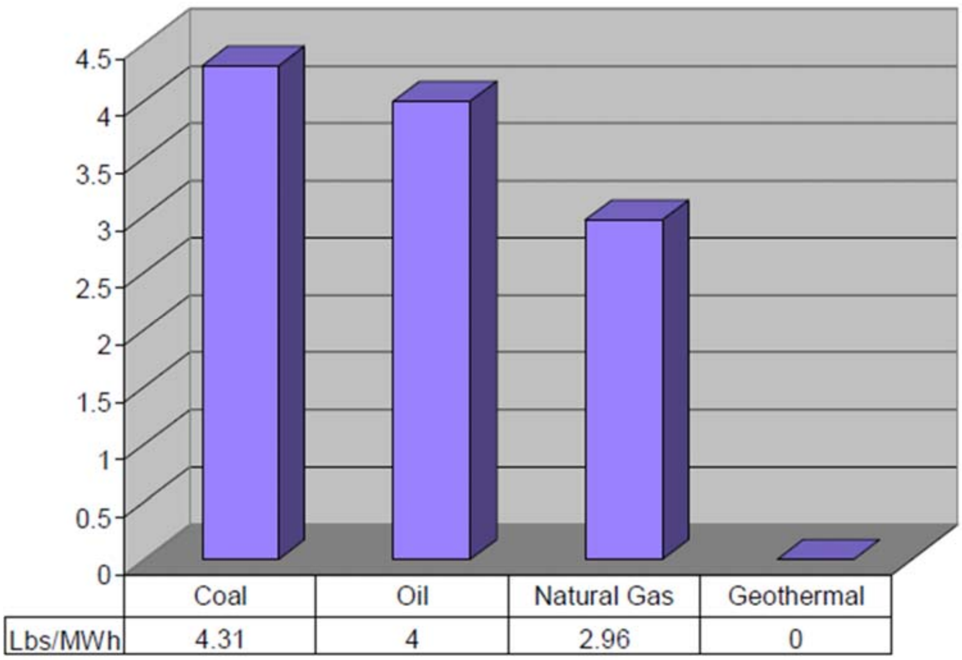
Environmental Impacts

- Land
  - Vegetation loss
  - Soil erosion
  - Landslides
- Air
  - Slight air heating
  - Local fogging
- Ground
  - Reservoir cooling
  - Seismicity (tremors)
- Water
  - Watershed impact
  - Damming streams
  - Hydrothermal eruptions
  - Lower water table
  - Subsidence
- Noise

- **Benign overall**

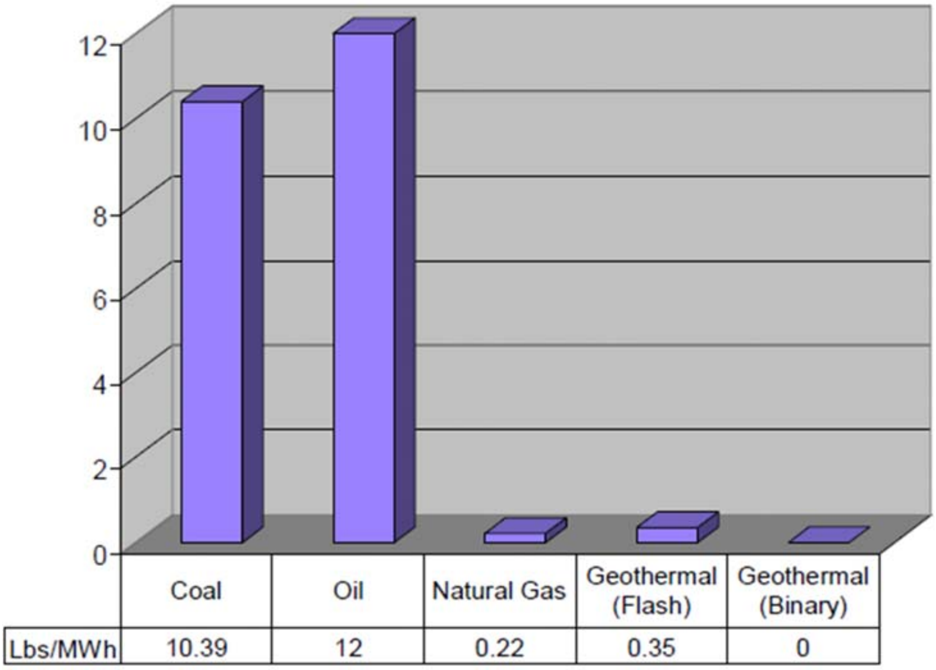
Environmental Impacts

Nitrogen Oxide Comparison



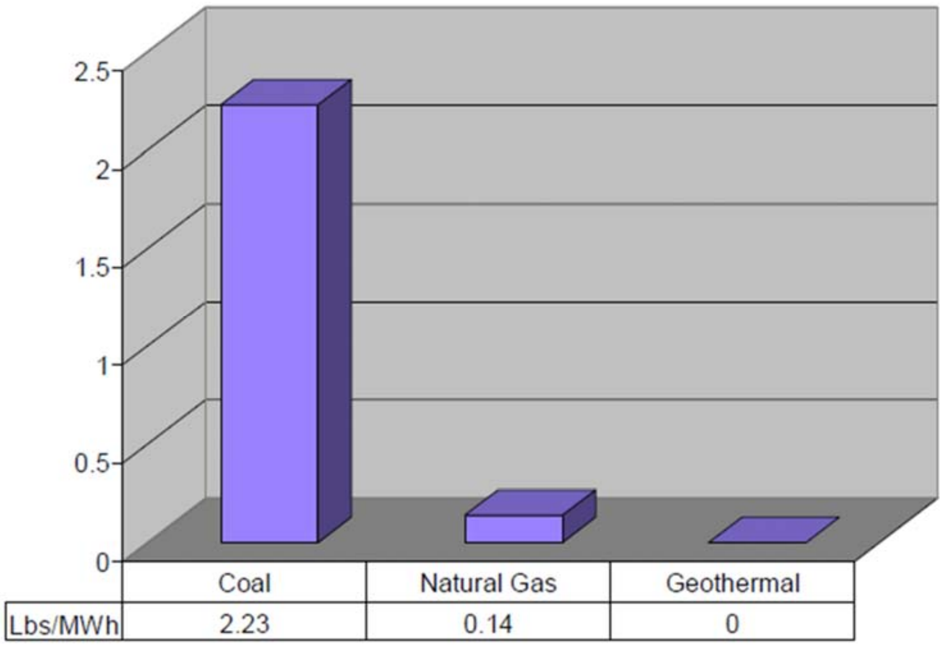
Environmental Impacts

Sulfur Dioxide emissions



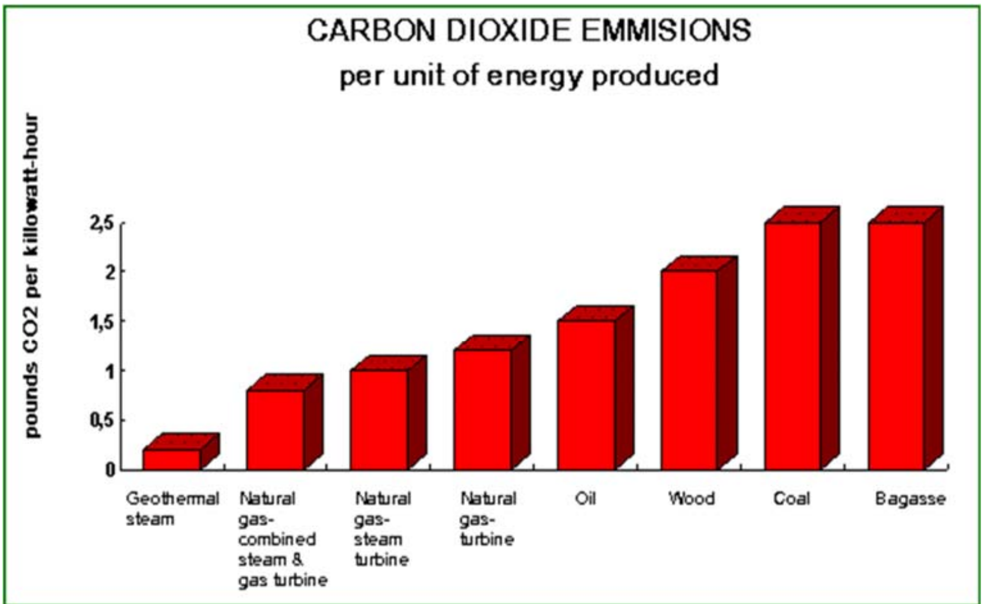
Environmental Impacts

Particulate Matter emissions



Environmental Impacts

Carbon Dioxide emissions



Comparison of CO_2 emissions between conventional energy systems and geothermal plants to generate electricity

Environmental Impacts

Emissions

lbs per megawatt hour:	**Nitrogen Oxides**	**Sulfur Dioxide**	**Carbon Dioxide**	**Particulate Matter**
Coal	4.31	10.39	2191	2.23
Coal, life cycle emissions	7.38	14.8	not available	20.3
Oil	4	12	1672	not available
Natural Gas	2.96	0.22	1212	0.14
EPA Listed Average of all U.S. Power Plants[97]	2.96	6.04	1392.5	not available
Geothermal (flash)	0	0.35	60	0
Geothermal (binary and flash/binary)	0	0	0	negligible
Geothermal (Geysers steam)	.00104	.000215	88.8	negligible

Environmental Impacts

Emission	Nitrogen oxide (NOx)	Sulfur Dioxide (SO_2)*	Particulate Matter (PM)	Carbon Dioxide (CO_2)
Sample Impacts	lung irritation, coughing, smog formation, water quality deterioration	wheezing, chest tightness, respiratory illness, ecosystem damage	asthma, bronchitis, cancer, atmospheric deposition, visibility impairment	global warming produced by carbon dioxide increases sea level, flood risk, glacial melting
Geothermal emissions (lb/MWh)	0	0 - 0.35	0	0 – 88.8
Coal emissions (lb/MWh)	4.31	10.39	2.23	2191
Emissions Offset by Geothermal Use (per yr)	32 thousand tons	78 thousand tons	17 thousand tons	16 million tons

- While geothermal plants do not emit sulfur dioxide directly, once hydrogen sulfide is released as a gas into the atmosphere, it eventually changes into sulfur dioxide and sulfuric acid. Therefore, any sulfur dioxide emissions associated with geothermal energy derive from hydrogen sulfide emissions

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Geothermal's Harmful Effects

- Brine can salinate soil if the water is not injected back into the reserve after the heat is extracted.
- Extracting large amounts of water can cause land subsidence, and this can lead to an increase in seismic activity. To prevented this the cooled water must be injected back into the reserve in order to keep the water pressure constant underground.
- Power plants that do not inject the cooled water back into the ground can release H_2S, the "rotten eggs" gas. This gas can cause problems if large quantities escape because inhaling too much is fatal.
- One well "blew its top" 10 years after it was built, and this threw hundreds of tons of rock, mud and steam into the atmosphere.
- There is the fear of noise pollution during the drilling of wells.

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Economics of Geothermal

Cost Factors

- Temperature and depth of resource
- Type of resource (steam, liquid, mix)
- Available volume of resource
- Chemistry of resource
- Permeability of rock formations
- Size and technology of plant
- Infrastructure (roads, transmission lines)

Costs of Geothermal Energy

- Costs highly variable by site
  - Dependent on many cost factors
- High exploration costs
- High initial capital, low operating costs
  - Fuel is "free"
- Significant exploration & operating risk
  - Adds to overall capital costs
  - "Risk premium"

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Economics of Geothermal

Cost of Water & Steam

	Cost (US $/ tonne of steam)	Cost (US ¢/tonne of hot water)
High temperature (>150°C)	3.5-6.0	
Medium Temperature (100-150°C)	3.0-4.5	20-40
Low Temperature (<100°C)		10-20

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Economics of Geothermal

Cost of Geothermal Power

	Unit Cost (US ¢/kWh) High Quality Resource	Unit Cost (US ¢/kWh) Medium Quality Resource	Unit Cost (US ¢/kWh) Low Quality Resource
Small plants (<5 MW)	5.0-7.0	5.5-8.5	6.0-10.5
Medium Plants (5-30 MW)	4.0-6.0	4.5-7	Normally not suitable
Large Plants (>30 MW)	2.5-5.0	4.0-6.0	Normally not suitable

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Economics of Geothermal

Direct Capital Costs

Plant Size	High Quality Resource	Medium Quality Resource	Low Quality Resource
Small plants (<5 MW)	Exploration : US$400-800 Steam field:US$100-200 Power Plant:US$1100-1300 **Total: US$1600-2300**	Exploration : US$400-1000 Steam field:US$300-600 Power Plant:US$1100-1400 **Total: US$1800-3000**	Exploration : US$400-1000 Steam field:US$500-900 Power Plant:US$1100-1800 **Total:US$2000-3700**
Med Plants (5-30 MW)	Exploration : US$250-400 Steamfield:US$200-US$500 Power Plant: US$850-1200 **Total: US$1300-2100**	Exploration: : US$250-600 Steam field:US$400-700 Power Plant:US$950-1200 **Total: US$1600-2500**	Normally not suitable
Large Plants (>30 MW)	Exploration:: US$100-200 Steam field:US$300-450 Power Plant:US$750-1100 **Total: US$1150-1750**	Exploration : US$100-400 Steam field:US$400-700 Power Plant:US$850-1100 **Total: US$1350-2200**	Normally not suitable

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Economics of Geothermal

Indirect Costs

- Availability of skilled labor
- Infrastructure and access
- Political stability
- Indirect Costs
  - Good: 5-10% of direct costs
  - Fair: 10-30% of direct costs
  - Poor: 30-60% of direct costs

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Economics of Geothermal

Operating/Maintenance Costs

	O&M Cost (US c/KWh) Small plants (<5 MW)	O&M Cost (US c/KWh) Medium Plants (5-30 MW)	O&M Cost (US c/KWh) Large Plants(>30 MW)
Steam field	0.35-0.7	0.25-0.35	0.15-0.25
Power Plant	0.45-0.7	0.35-0.45	0.25-0.45
Total	**0.8-1.4**	**0.6-0.8**	**0.4-0.7**

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Geysers Geothermal Plant

Geysers Geothermal Plant

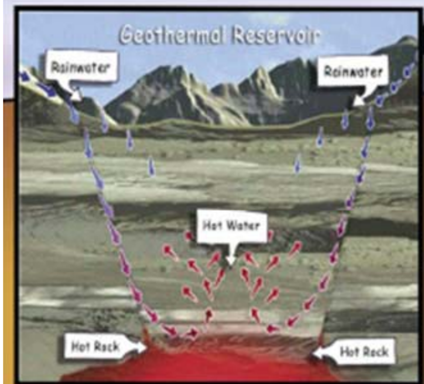
Geothermal Power Examples

Table 9.1 Geothermal power generation around the end of the twentieth century

Nation	1995 MW_e	2000 MW_e	2005 (est. MW_e)
Argentina	0.67	0	n/a
Australia	0.17	0.17	n/a
China	28.78	29.17	n/a
Costa Rica	55.0	142.5	161.5
El Salvador	105.0	161	200
Ethipoia	0	8.52	8.52
France	4.2	4.2	20
Guatemala	0	33.4	33.4
Iceland	50.0	170	186
Indonesia	309.75	589.5	1987.5
Italy	631.7	785	946
Japan	413.7	546.9	566.9
Kenya	45.0	45	173
Mexico	753.0	755	1080
New Zealand	286.0	437	437
Nicaragua	70.0	70	145
Philippines	1227.0	1909	2673
Portugal	5.0	16	45
Russia	11.0	23	125
Thailand	0.3	0.3	0.3
Turkey	20.4	20.4	250
USA	2816.7	2228	2376
Totals	**6833**	**7974**	**11 414**

(from Huttrer, 2000)

Geothermal Energy



Geothermal Energy is heat (thermal) derived from the earth (geo). It is the thermal energy contained in the rock and fluid that fills the fractures and pores within the rock in the earth's crust. Visual, surface indications of the presence of geothermal activity include geysers, fumaroles, mudpots, hot springs and volcanoes.

Depending on the geophysical conditions that exist at a geothermal site, different technologies can be used to utilize the geothermal energy. Modern applications include greenhouses, aquaculture, home and business heating, and electricity generation.

Electricity generation is accomplished by drilling wells into the earth to tap into the geothermal energy reservoirs. The thermal energy available in the reservoirs can be used to power electricity generation equipment.

One method of generating electricity is by using the geothermal energy to power a Binary-cycle Power Plant. This type of plant is used for relatively low temperature geothermal reservoirs in the range of 250º to 300º F. In this plant, geothermal waters are passed through a heat exchanger to heat a secondary working fluid that vaporizes at a lower temperature than water. The working fluid vapor spins a turbine/generator and is condensed back to liquid before being re-vaporized in the heat exchanger again. The heat-depleted geothermal water is injected back into the geothermal reservoir.

Other methods for generating electricity include Flash Steam, Dry Steam and Hot Dry Rock power plants.