Ειδικά κεφάλαια παραγωγής ενέργειας

Ενότητα 6: Geothermal Energy

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Τμήμα Μηχανολόγων Μηχανικών

ΕΠΙΧΕΙΡΗΣΙΑΚΟ ΠΡΟΓΡΑΜΜΑ ΕΚΠΑΙΔΕΥΣΗ ΚΑΙ ΔΙΑ ΒΙΟΥ ΜΑΘΗΣΗ
Ευρωπαϊκή Ένωση
ΕΣΠΑ 2007-2013

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- Το παρόν εκπαιδευτικό υλικό έχει αναπτυχθεί στα πλαίσια του εκπαιδευτικού έργου του διδάσκοντα.
- Το έργο «**Ανοικτά Ψηφιακά Μαθήματα στο Πανεπιστήμιο Δυτικής Μακεδονίας**» έχει χρηματοδοτήσει μόνο τη αναδιαμόρφωση του εκπαιδευτικού υλικού.
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επένδυση στην κοινωνία της γνώσης
ΥΠΟΥΡΓΕΙΟ ΠΑΙΔΕΙΑΣ ΚΑΙ ΘΡΗΣΚΕΥΜΑΤΩΝ
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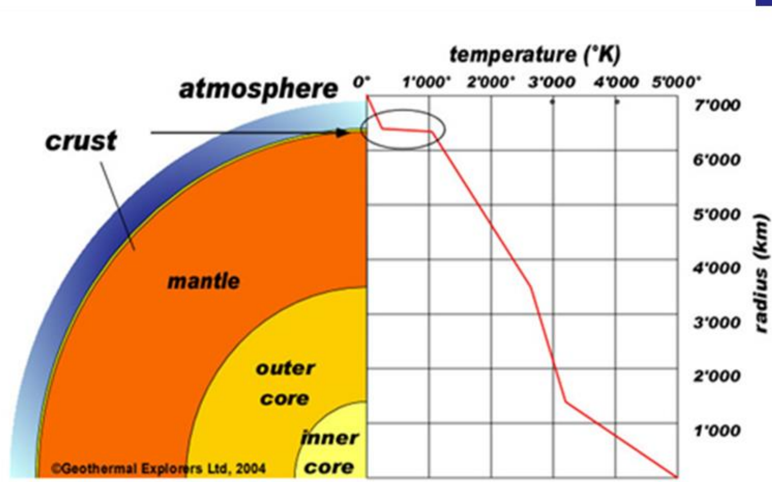
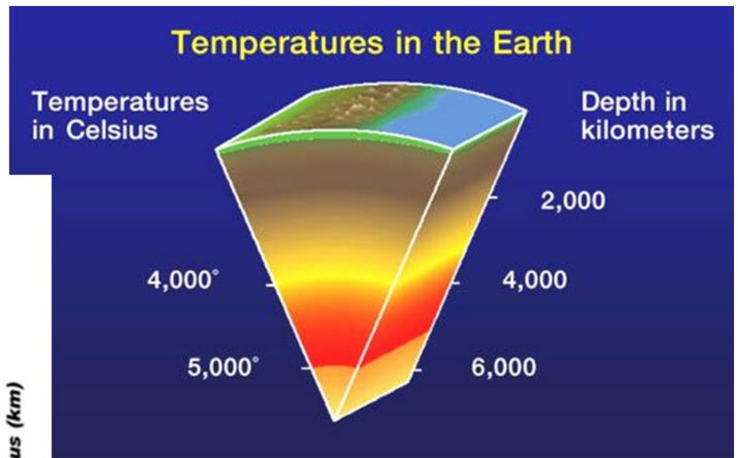
ΕΣΠΑ 2007-2013
πρόγραμμα για την ανάπτυξη
ΕΥΡΩΠΑΪΚΟ ΚΟΙΝΩΝΙΚΟ ΤΑΜΕΙΟ
Με τη συγχρηματοδότηση της Ελλάδας και της Ευρωπαϊκής Ένωσης

Geothermal Energy

Definition:

Geothermal Energy is energy stored in the form of heat beneath the surface of the solid earth.



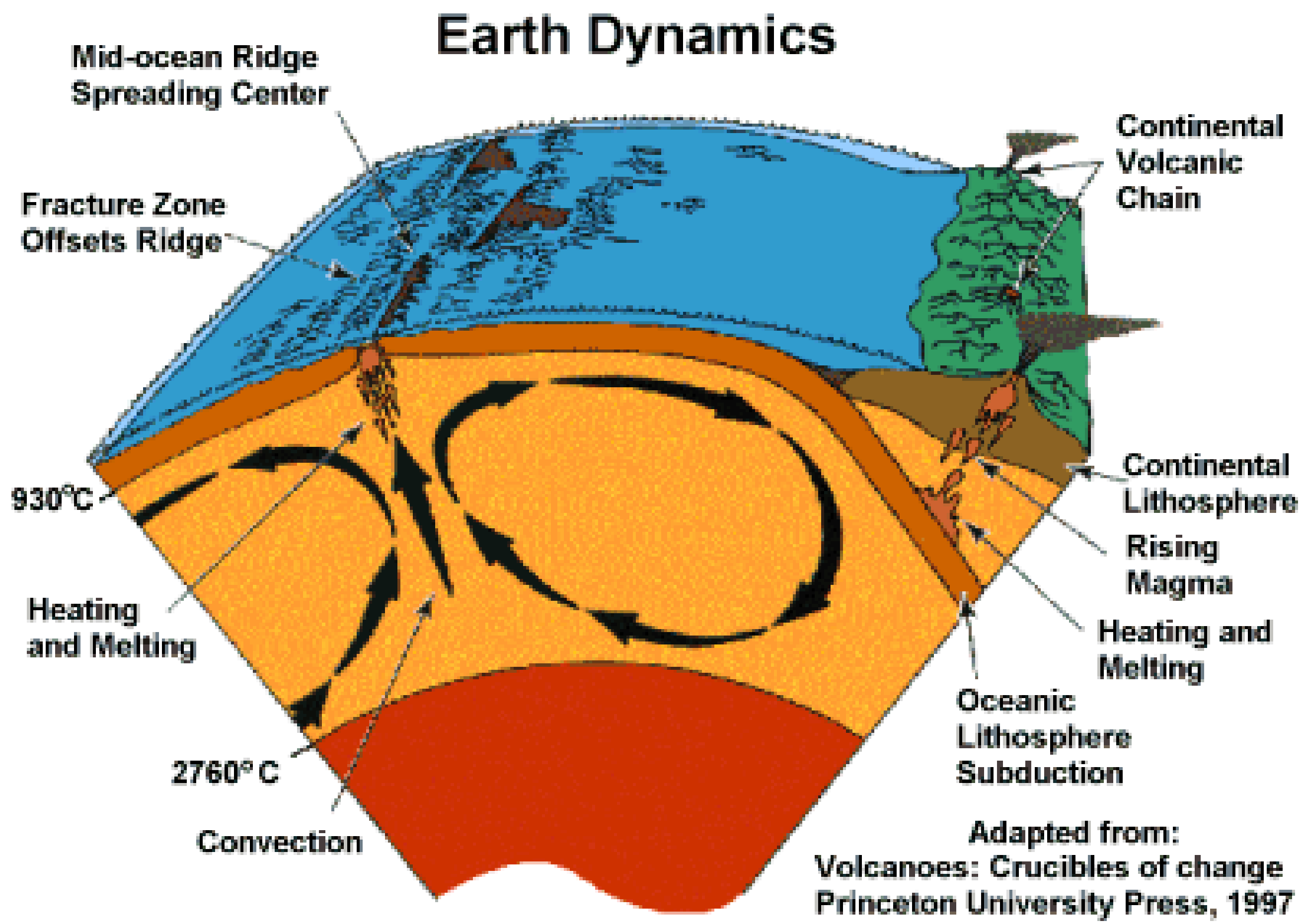


Graph from Geothermal Education Office, California

Heat from the Earth's Core

- Earth's core maintains temperatures in excess of 5000°C.
  - Heat is coming from the gradual radioactive decay of elements.
- Heat energy continuously flows from hot earth's core.
  - Conductive heat flow.
  - Convective flows of molten mantle beneath the crust.
- Mean heat flux at earth's surface .
  - 16 kilowatts of heat energy per square kilometer
  - Dissipates to the atmosphere and space.
  - Tends to be strongest along tectonic plate boundaries.
- Volcanic activity transports hot material close to surface.
  - Only a small fraction of molten rock actually reaches surface.
  - Most is left at depths of 5-20 km beneath the surface.
- Hydrological convection forms high temperature geothermal systems at shallow depths of 500-3000m. http:/ /www.worldbank.org/html/fpd/energy/geothermal/technology.htm

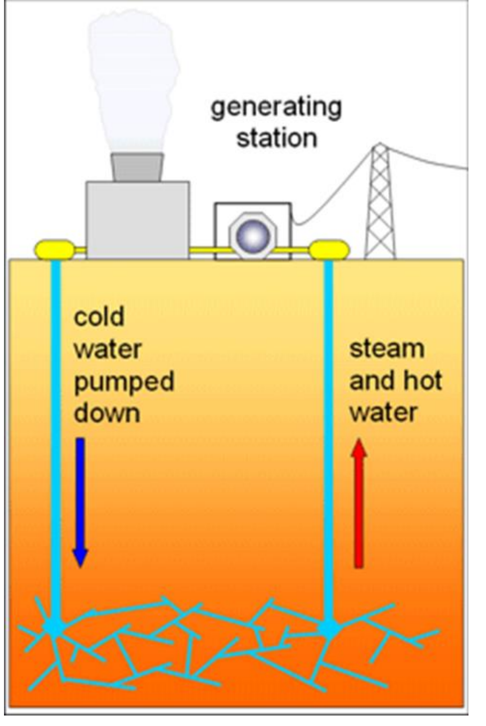
Earth Dynamics



Geothermal Energy – energy from the Earth

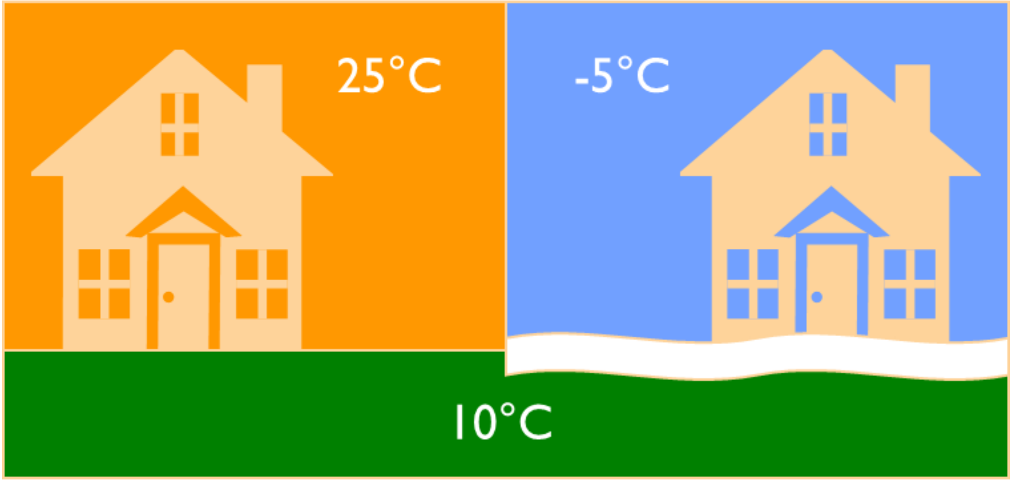
Deep underground, the Earth's rocks are naturally very hot. We can turn their heat energy into electrical energy to use in our homes – we call this 'geothermal energy'.

1. Cold water is pumped below the ground.
2. Hot rocks heat the water, turning it into steam.
3. The steam is used to generate electricity.



\+ Renewable.
\+ No pollution, because nothing gets burned.
\+ Doesn't damage the environment.
– Very few places in the world where you can do this.
– Costs a lot of money to drill deep into the ground.

What is geothermal energy?

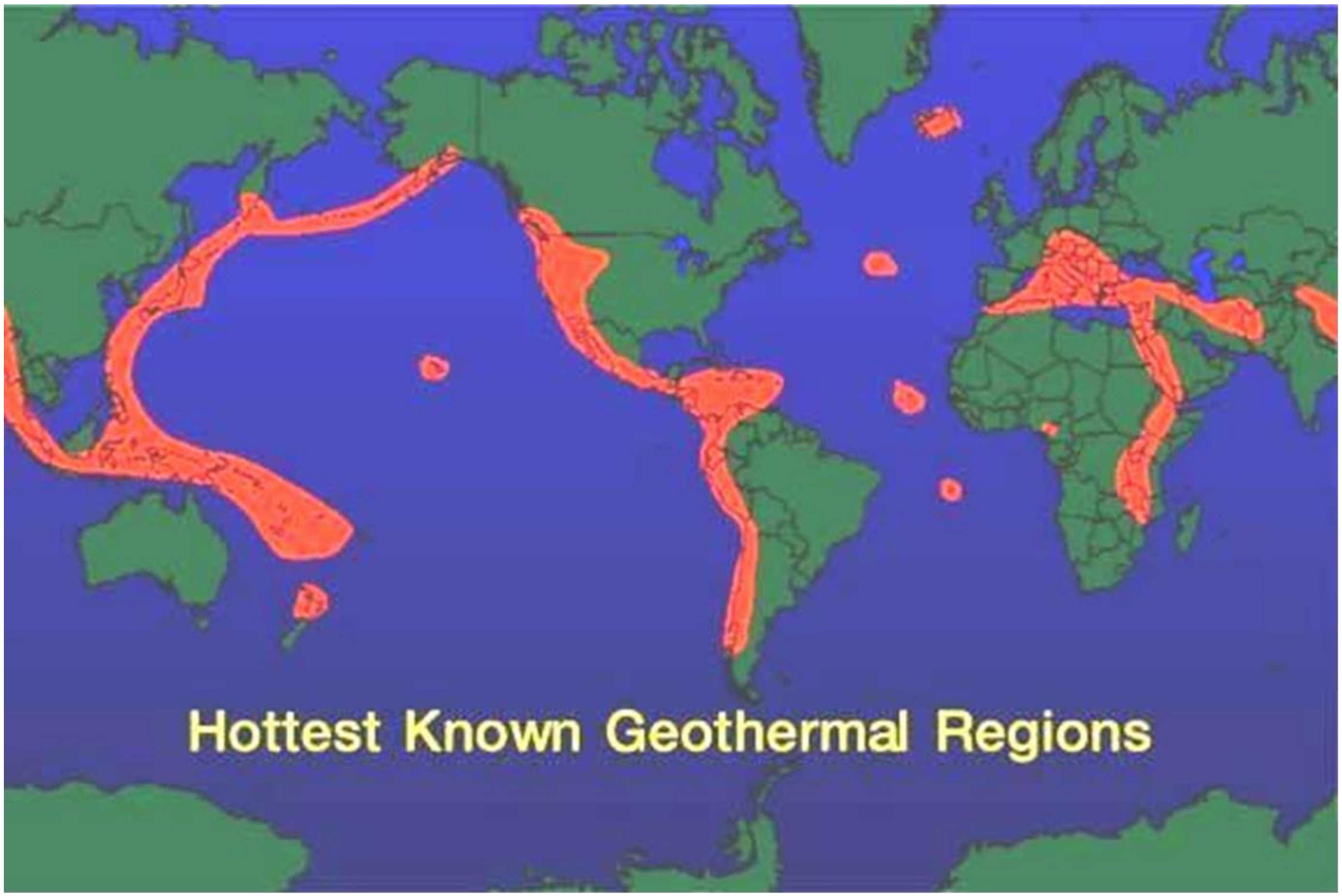


it’s energy created by the sun and stored in the earth .

The temperature underground is constant between 5°C and 10°C.

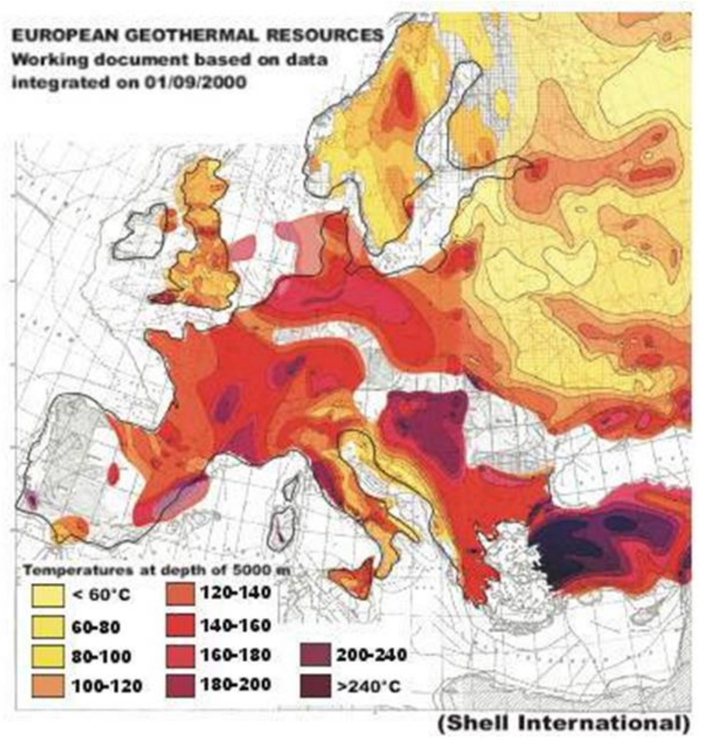
Warmer than the air in the winter and **cooler** than the air in the summer.

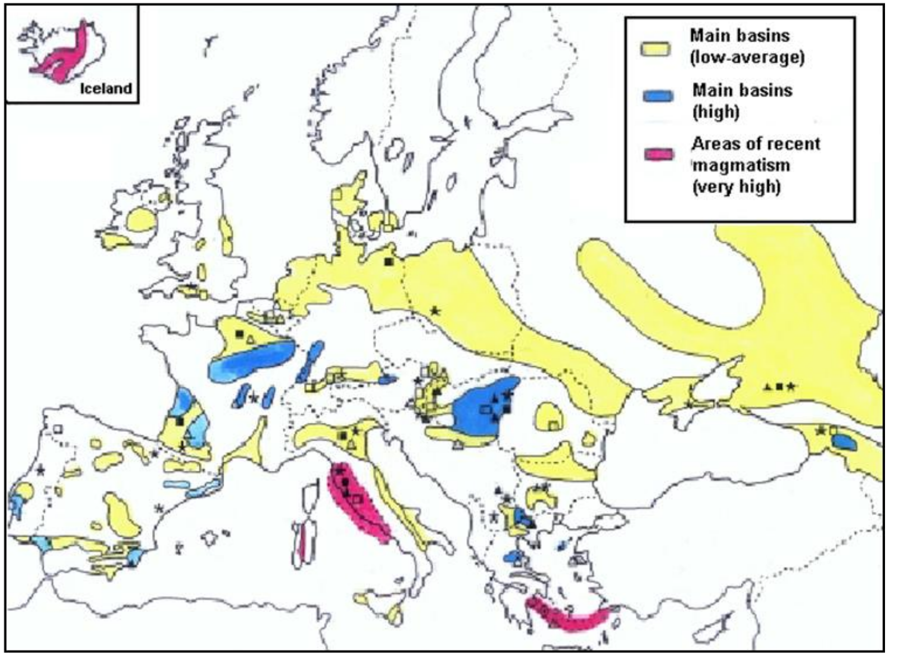
High-Enthalpy Geothermal Energy world-wide



Graph from Geothermal Education Office, California

The Potential of Geothermal Energy in EU





Potential after Shell-study.

Geysers

Clepsydra Geyser in Yellowstone.

A geyser is a type of hot spring that erupts periodically, ejecting a column of hot water and steam into the air.
The formation of geysers requires a favorable hydrogeology which exists in only a few places on Earth, and so they are fairly rare phenomena.
Geyser eruptive activity may change or cease due to ongoing mineral deposition within the geyser plumbing, exchange of functions with nearby hot springs, earthquake influences, and human intervention.

http://en.wikipedia.org/wiki/Geyser

Hot Springs

http://www.eia.doe.gov/cneaf/solar.renewables/page/geothermal/geothermal.html

Fumaroles

Clay Diablo Fumarole (CA)

White Island Fumarole New Zealand

CDF's vent temperature is measured a few times each year, has remained fairly stable between 92 and 94 degrees.

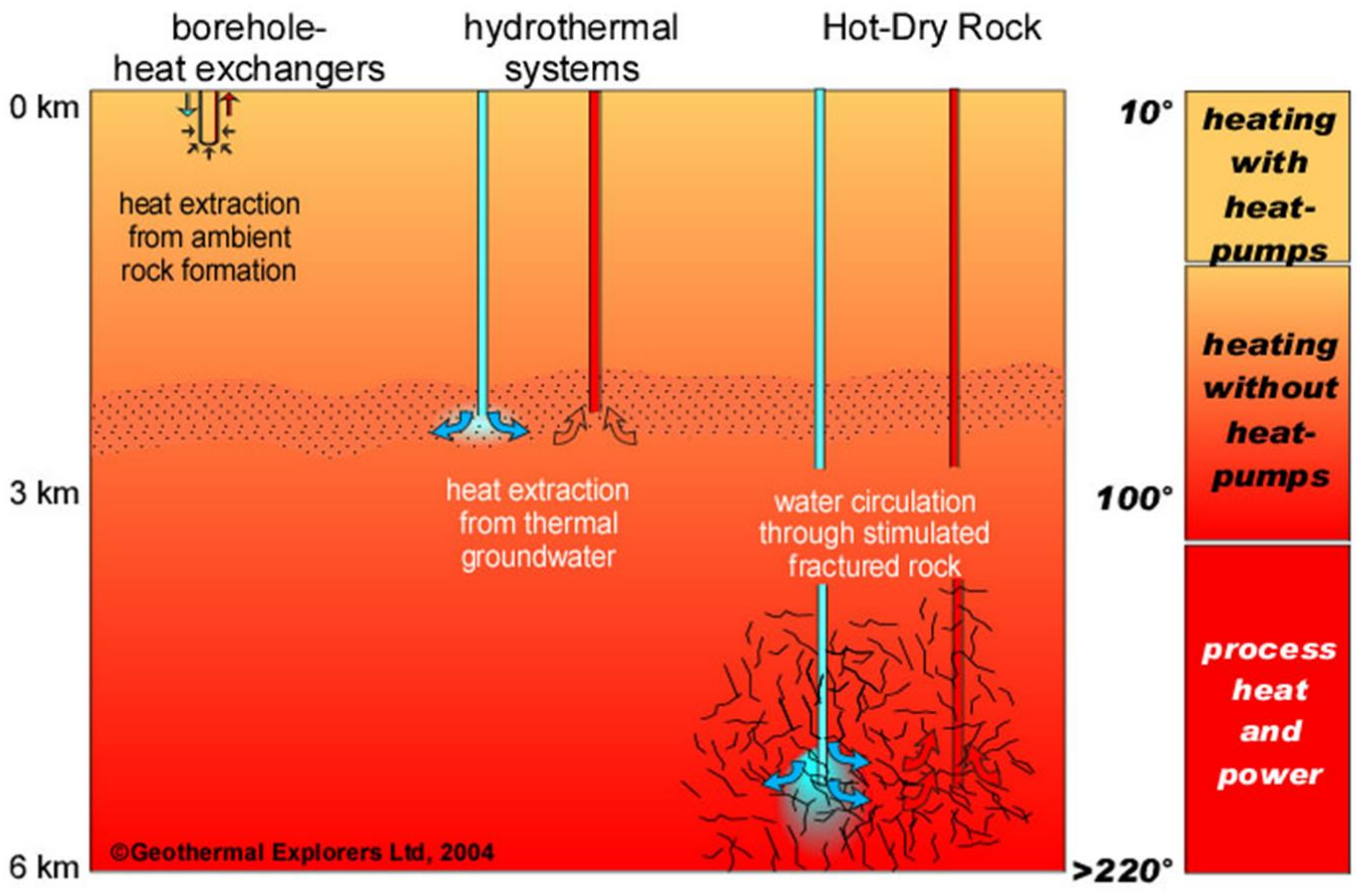
http://lvo.wr.usgs.gov/cdf_main.htm

http://volcano.und.edu/vwdocs/volc_images/img_white_island_fumerole.html

Definitions: Geothermal Energy

- HDR – Hot, dry rock: has no natural steam but may receive injected water to produce steam.
- Head – the height of water – the hydraulic height of the water (1 psi = 2.31 ft H_2O).
- Heat Quality – the temperature of the heat.
- Ground Source Heat Pump – extracts from ground or rejects heat to ground.

Methods of Heat Extraction



http://www.geothermal.ch/eng/vision.html

Extraction of Geothermal Fluids Cost Factors (1/2)

- The heat from a geothermal source is recovered by drilling.
- The flow can be spontaneous or can be assisted by pumping.
- The flux is proportional to ΔP between the reservoir and the pump at surface.
- For constant ΔP the geothermal fluid flux decreases slowly with time.

$$\Delta P = \frac{Q \times \mu}{4 \times \pi \times k \times h} \times \ln\left(\frac{2{,}246 \times k \times t}{\varphi \times \mu \times \sigma \times r^2}\right)$$

ΔP [Pa], Q [m^3/s], μ [viscosity, kg/m/s], k [reservoir's permeability, $m^3/m=m^2$].
h [reservoir's thickness, m], t [drilling time, s], ϕ [reservoir's porosity].
σ [fluid compressibility], r [borehole radius, m].

Extraction of Geothermal Fluids Cost Factors (2/2)

- The term k x h is the reservoir's "conductivity".
- The term Φ x σ x h is the "storage capacity .
- For two-phase fluid, the mass flow rate:

$$\frac{G \times H}{P^{-0,18}} = 0,765 \times 10^{6}$$

where: G is the mass flow rate of the two-phase geothermal fluid [kg/m^2/s].

H is the specific enthalpy of the two-phase geothermal fluid [kJ/kg].

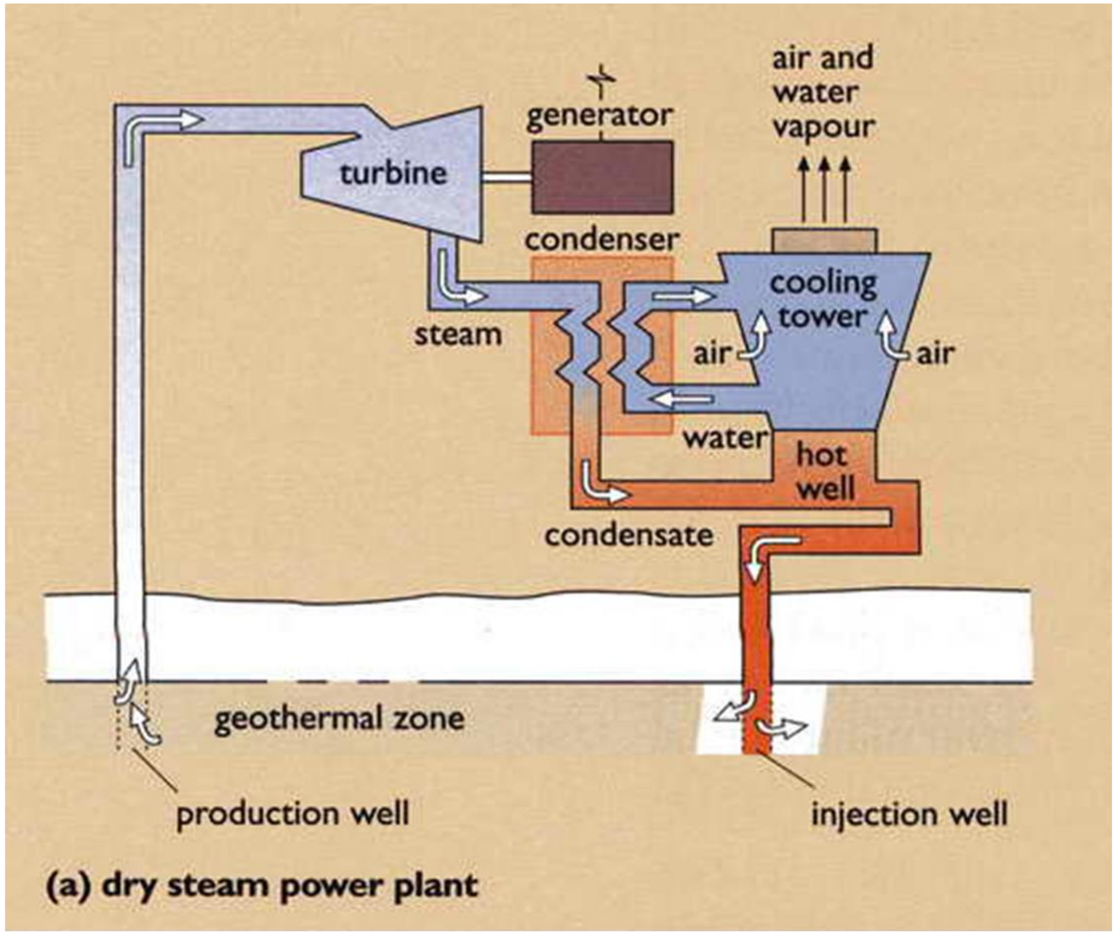
P is the ΔP between the reservoir and the wellhead [bar].

Dry Steam Power Plants

- "Dry" steam 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.

Boyle, *Renewable Energy*, 2nd edition, 2004

Dry Steam Schematic

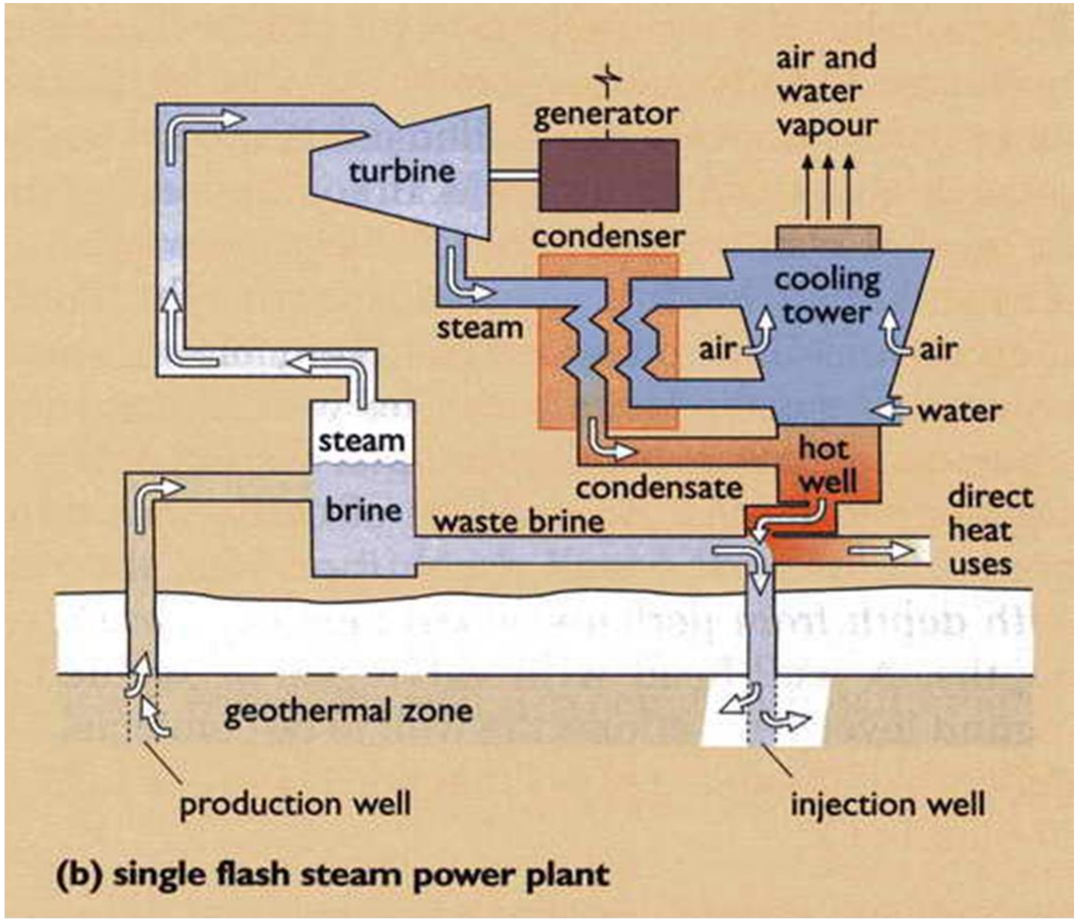


Boyle, *Renewable Energy*, 2nd edition, 2004

Single Flash Steam Power Plants

- Steam with water extracted from ground.
- Pressure of mixture drops at surface and more water “flashes” to steam – Undesired.
- Steam separated from water.
- Steam drives a turbine.
- Turbine drives an electric generator.
- Generate between 5 and 100 MW.
- Use 6 to 9 tonnes of steam per hour.

Single Flash Steam Schematic



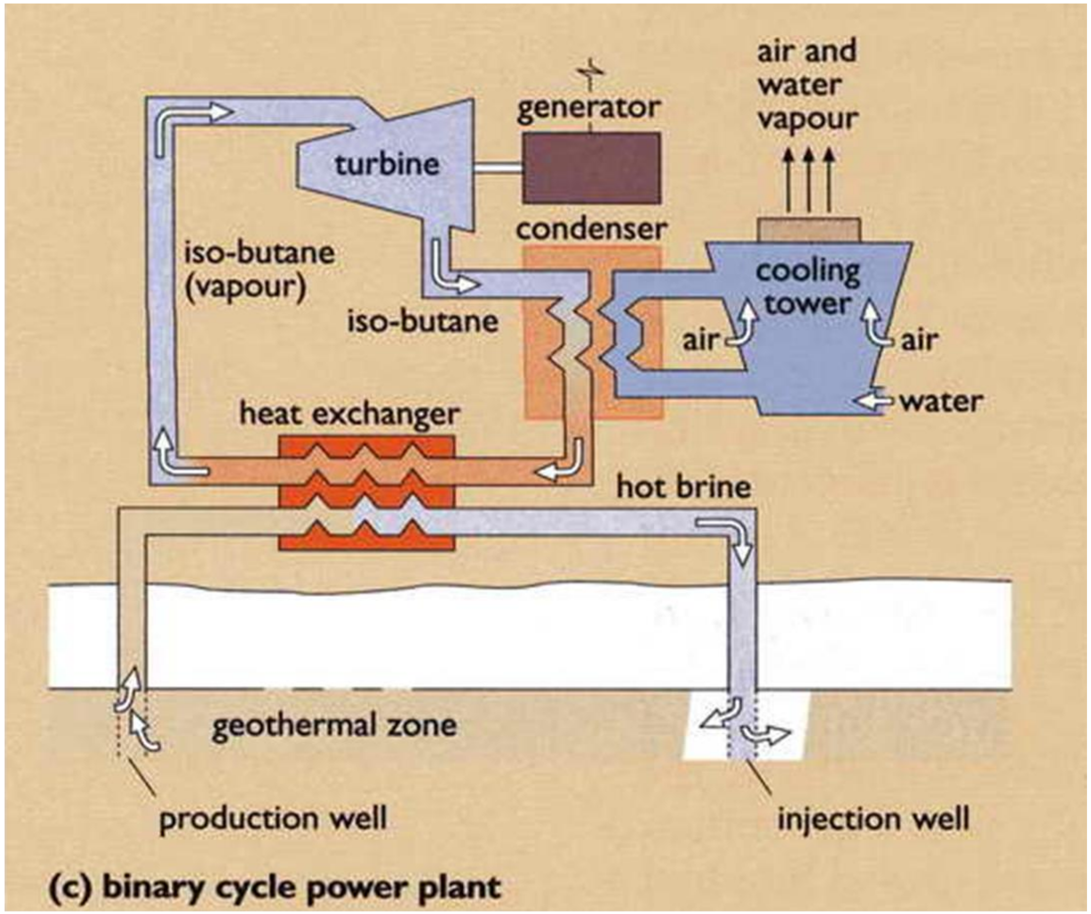
Boyle, *Renewable Energy*, 2nd edition, 2004

Binary Cycle Power Plants

- Low temps – 100^o and 150^{o}C.
- Use heat to vaporize organic liquid:
  - e.g., iso-butane, iso-pentane.
- Use vapor to drive turbine:
  - Causes vapor to condense.
  - Recycle continuously.
- Typically 7 to 12 % efficient.
- 0.1 – 40 MW units common.

http://www.worldenergy.org/wec-geis/publications/reports/ser/geo/geo.asp

Binary Cycle Schematic

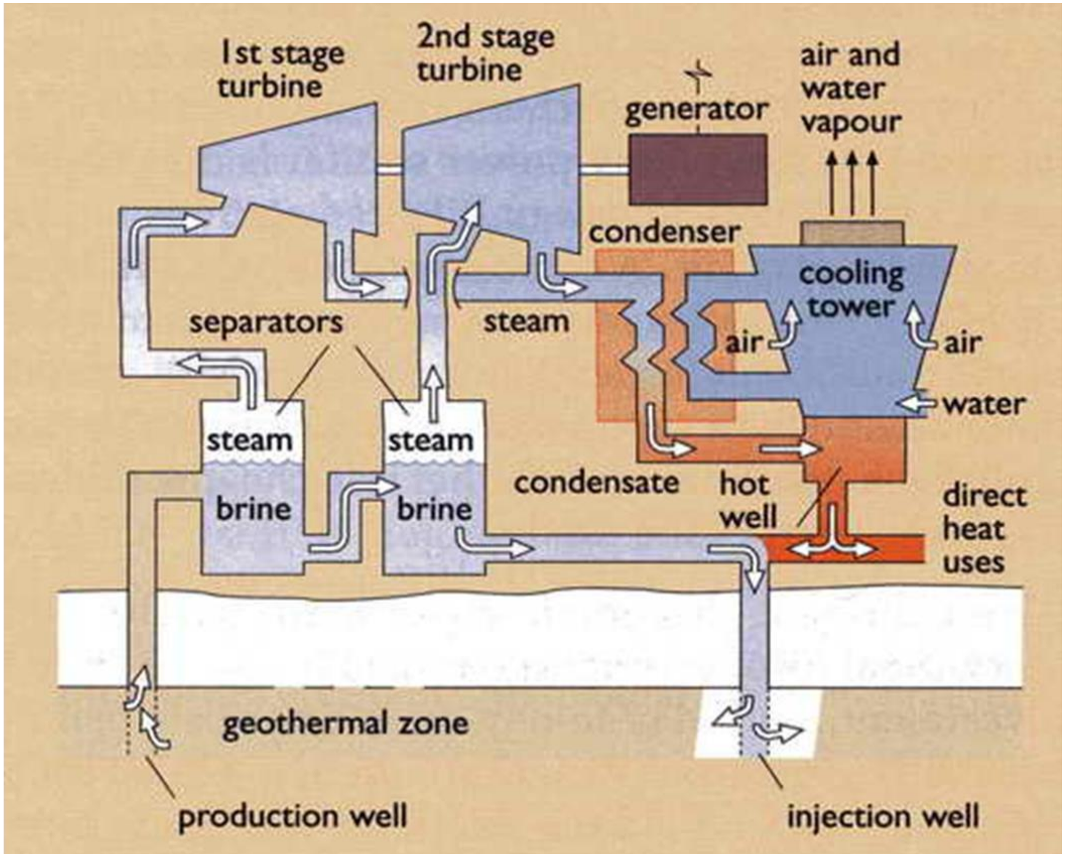


Boyle, *Renewable Energy*, 2nd edition, 2004

Double Flash Power Plants

- Similar to single flash operation.
- Un-flashed 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.

Double Flash Schematic



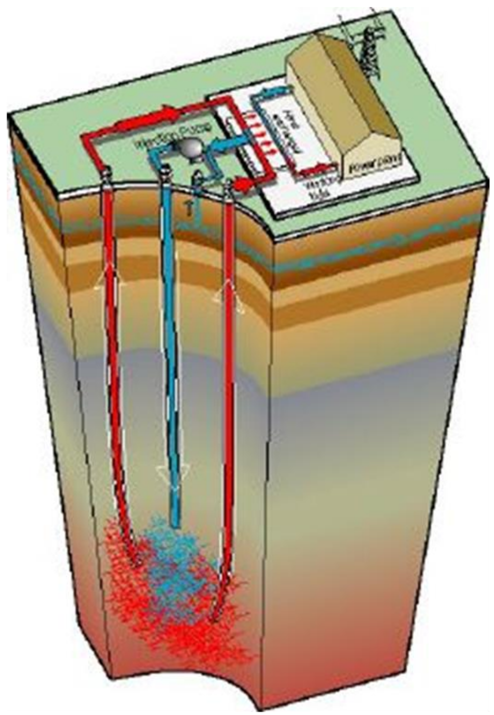
(d) double flash power plant

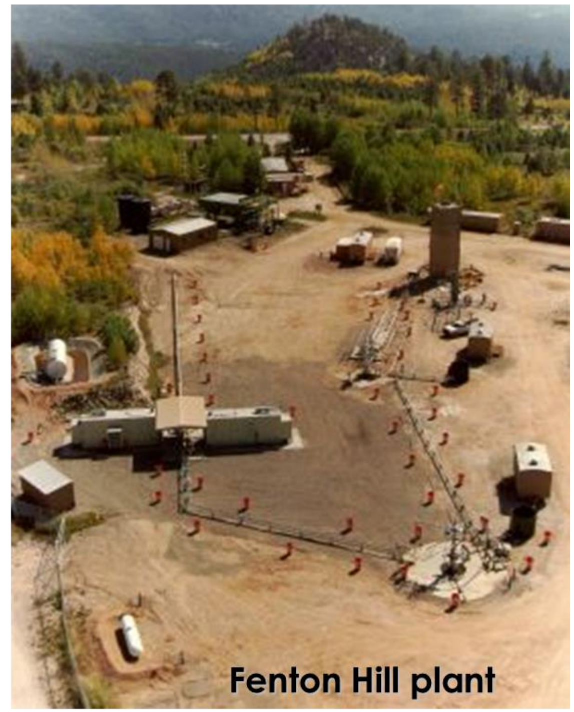
Boyle, *Renewable Energy*, 2nd edition, 2004

Hot Dry Rock Technology Cost Factors (1/2)

- Wells drilled 3-6 km into crust:
  - Hot crystalline rock formations.
- Water pumped into formations.
- Water flows through natural fissures picking up heat.
- Hot water/steam returns to surface.
- Steam used to generate power.

Hot Dry Rock
Technology Cost Factors (2/2)





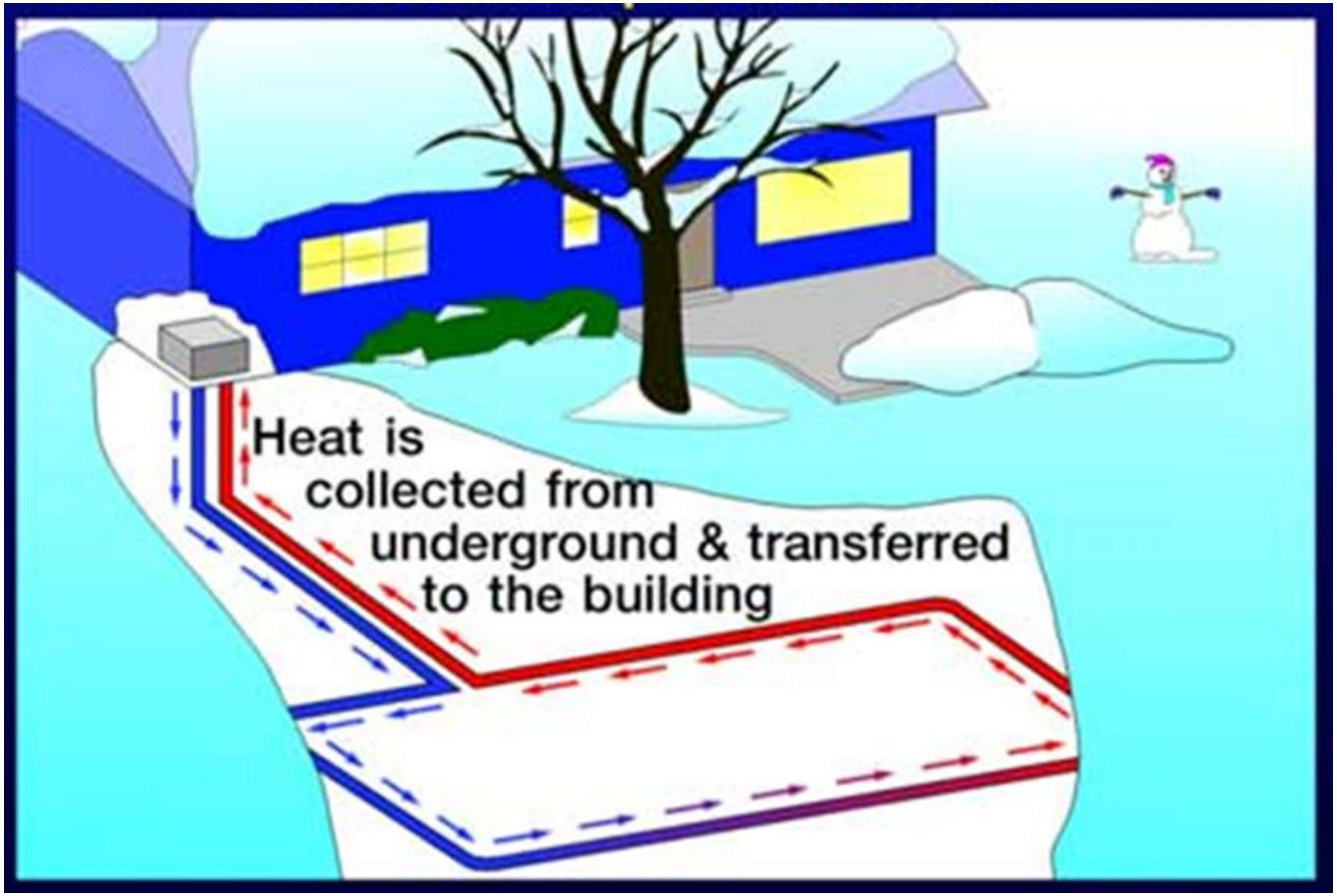
1 km^3 of hot rock has the energy content of 70,000 tonnes of coal.

http://www.ees4.lanl.gov/hdr/

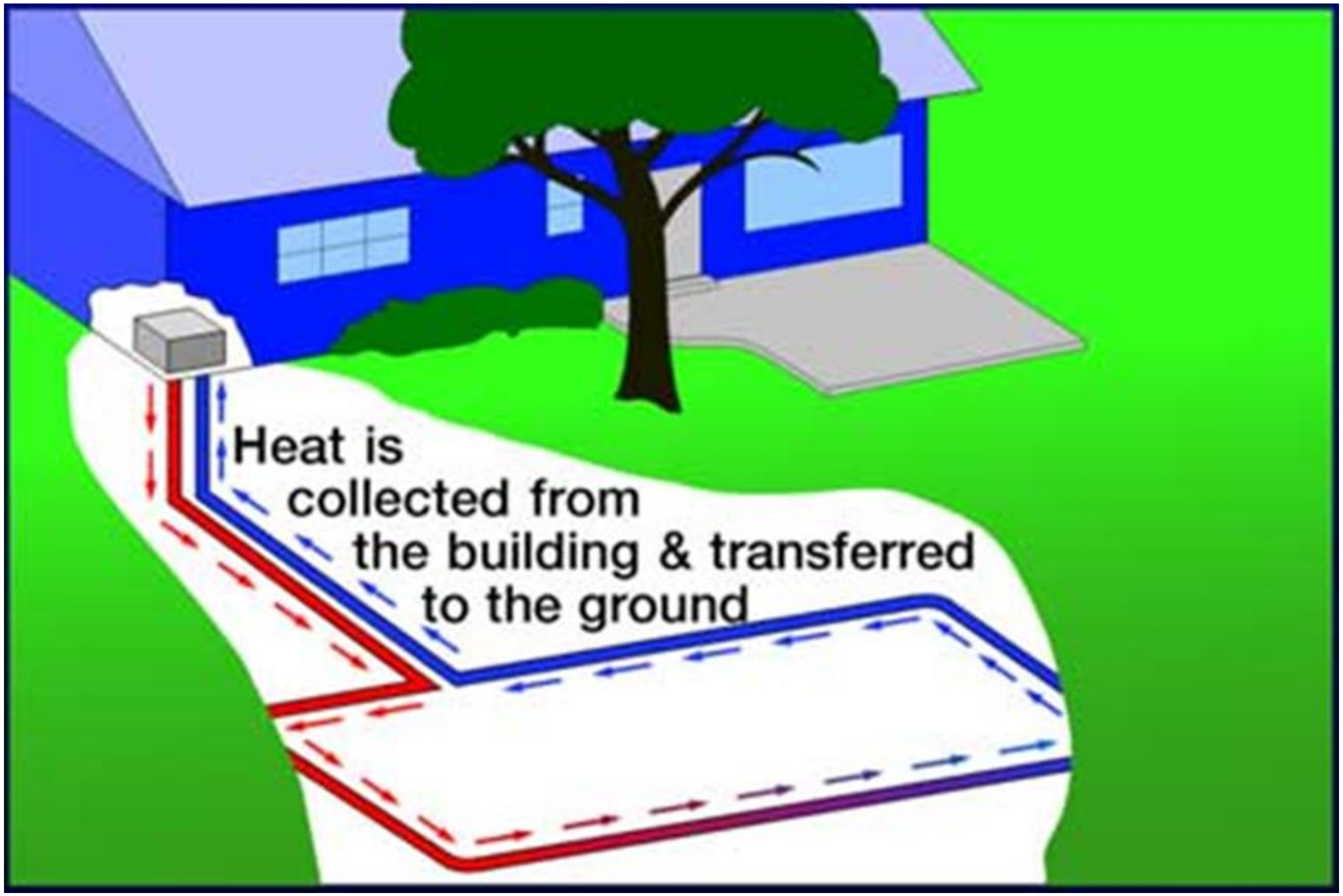
Low Temperature Heat Extraction/Rejection

- The classic use of earth/water is as a heat sink or source for air conditioning or heating.
- Pipes embedded in the earth carry refrigerant or water and conduct heat from the hotter to cooler substance.
- Since the earth (or water) has a high specific heat in comparison with air, there is good thermal transfer.
- In winter, heat is extracted from the earth by the chilled refrigerant, while in the summer, the hot refrigerant conducts heat to the earth.
- Houses have been built partially underground to moderate the winter and summer temperatures.

Heat Pump in Winter



Heat Pump in Summer



Technological Issues

- Geothermal fluids can be corrosive:
  - Contain gases such as hydrogen sulphide.
  - Corrosion, scaling.
- Requires careful selection of materials and diligent operating procedures.
- Typical capacity factors of 85-95%.

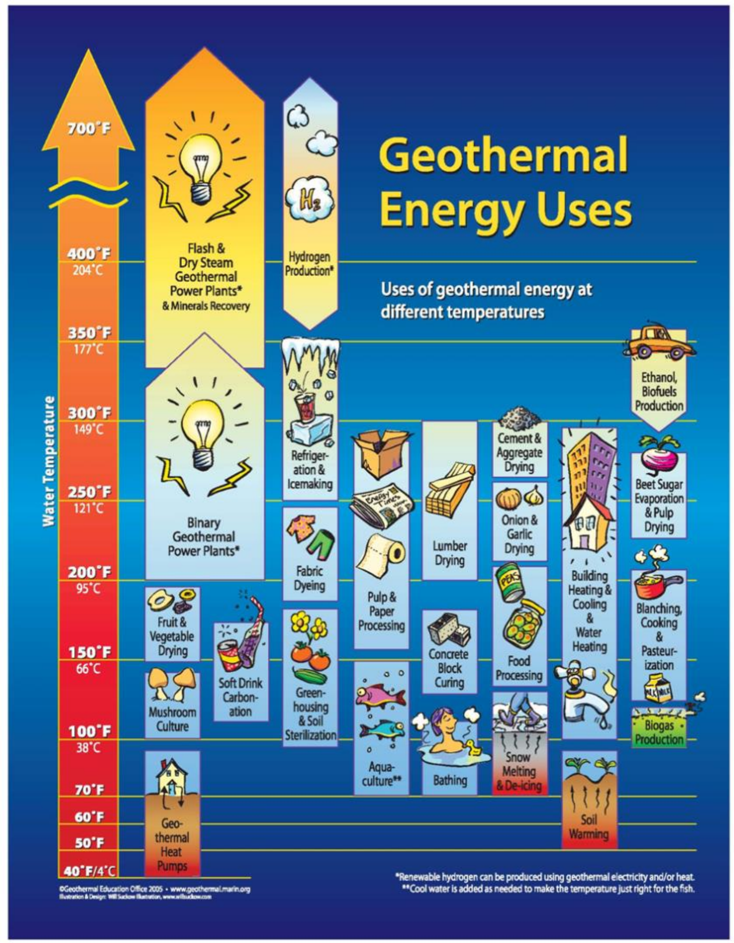
http://www.worldbank.org/html/fpd/energy/geothermal/technology.htm

Cost Factors (1/2)

- 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).

http://www.worldbank.org/html/fpd/energy/geothermal/cost_factor.htm

Cost Factors (2/2)



Geothermal application in the food industry

Geothermal tomato drying in Northern Greece

The finished product

Example 3: Geothermal Electricity Production Cost Factors (1/3)

- A geothermal reservoir is at a temperature of 300 °C and contains saturated water. For geothermal electricity production from this reservoir a steam turbine with a condenser operating at 0.1 bar is used. If the drilling hole radius is 15 cm, calculate the electrical power and efficiency in the cases where the wellhead and the separator operate at 10 bar.
- The specific enthalpy of the geothermal fluid is 1,344 kJ/kg (considered as saturated liquid at the temperature of the reservoir). For this drilling cross-section and for the above given pressure, the volumetric flow rate of the geothermal fluid is calculated from:

P, bar	10
G, kg/m²/s	376
Q, tn/h	43

$$\frac{\mathbf{G} \times H}{P^{-0,18}} = 0,765 \times 10^{6}$$

Example 3: Geothermal Electricity Production Cost Factors (2/3)

The specific enthalpy and entropy of saturated water, and steam at the separator conditions can be derived from thermodynamic tables:

	enthalpy		entropy
	steam	water	steam
	kJ/kg	kJ/kg	kJ/kg/K
10 bar	2778.1	762.81	6.5865

Assuming that the two-phase geothermal fluid exchanges no energy when rising through the drilling hole, the overall enthalpy of the separator will still be equal to 1,344 kJ/Kg, and if x is the percentage of steam in the separator, then x will be equal to:

1344 = 2778.1*x + 762.81*(1 – x) ⇔ x = 581.19 / 2015.29 = 0.288.

and the amount of steam supplied to the turbine will be:

0.288 * 43 = 12.4 tn/h with enthalpy equal to:

12.4 * 1000 * 2778.1 / 3600 = 9.56 MJ/s.

Example 3: Geothermal Electricity Production Cost Factors (3/3)

At the outlet of the turbine, at pressure equal to 0.1 bar, the entropy of saturated water and steam are 0.6493 and 8.1502 kJ/kg/s and the enthalpy of saturated water and steam is 191.83 and 2584.7 kJ/kg, respectively. If the operation of the turbine is isentropic:

6.5865 = 8.1502 * x + 0.6493 * (1 – x) ⇔ x = 5.937 /7.5009 = 0.792.
and the heat reaching the condenser will be:
12.4 * (1000 / 3600) * (0.792 * 2584.7 + 0.208 * 191.83) = 7.18 MJ/s.

Then the power of the steam turbine will be:
0.8 * (9.56 – 7.18) = 2.38 MW.
and the efficiency of the geothermal setup will be equal:
2.38 / (1344 * 43 * 1000 / 3600) = 14.8 %.

Τέλος Ενότητας