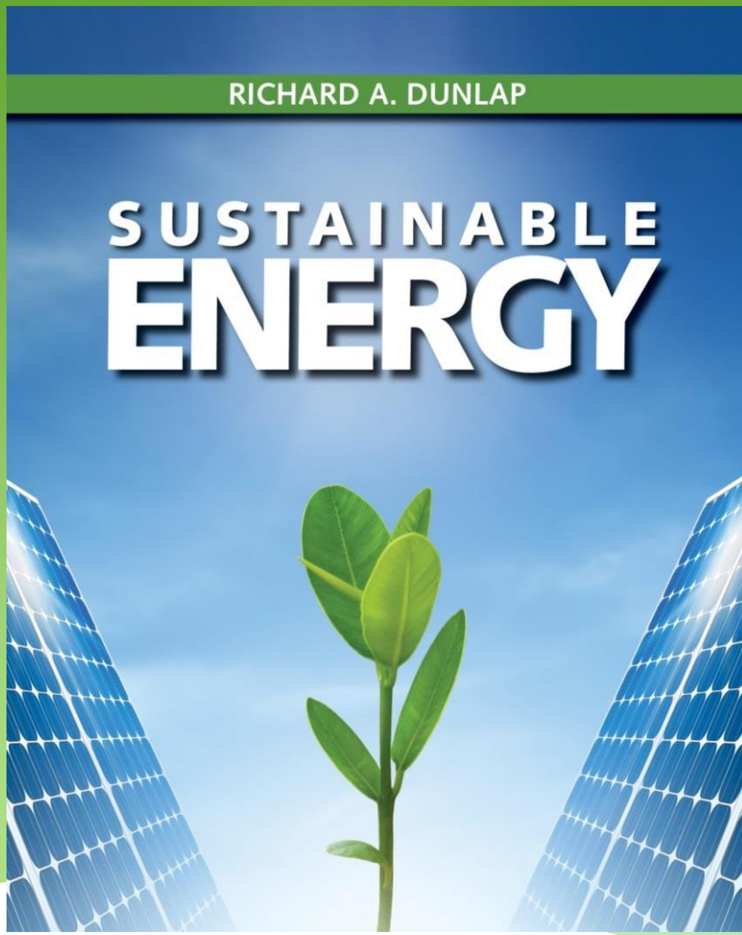
Sustainable Energy



Chapter 15

- Geothermal Energy

Learning Objectives

- The reasons for geothermal energy.
- The types and distribution of geothermal energy resources.
- The direct use of geothermal heat.
- The types of geothermal electric generating facilities.
- The use of geothermal energy worldwide.
- The sustainability and environmental consequences of geothermal energy use.

The interior of the earth

The interior of the earth consists of various layers:

- crust
- outer mantle
- inner mantle
- outer core
- inner core

Schematic of the interior of the earth

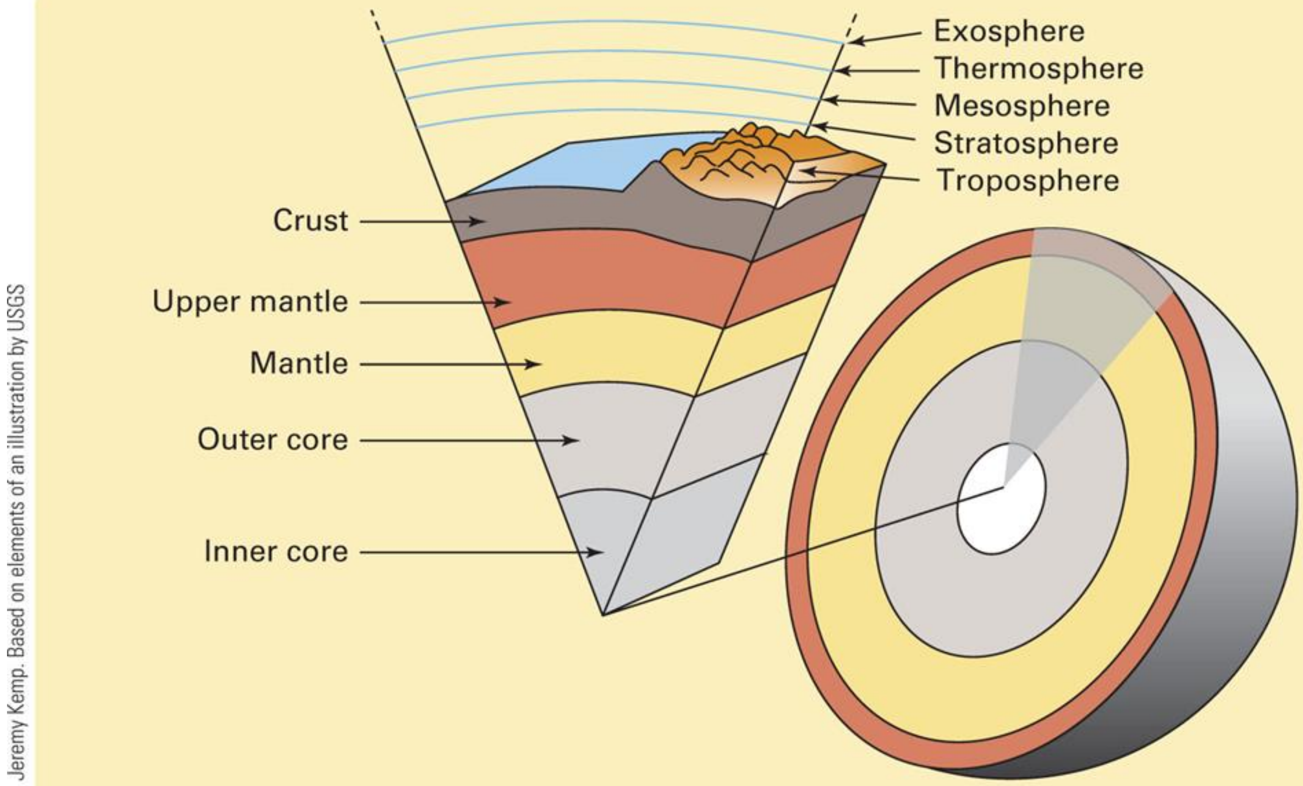


Figure 15.1: The internal structure of the earth.

Dimensions of the earth's layers

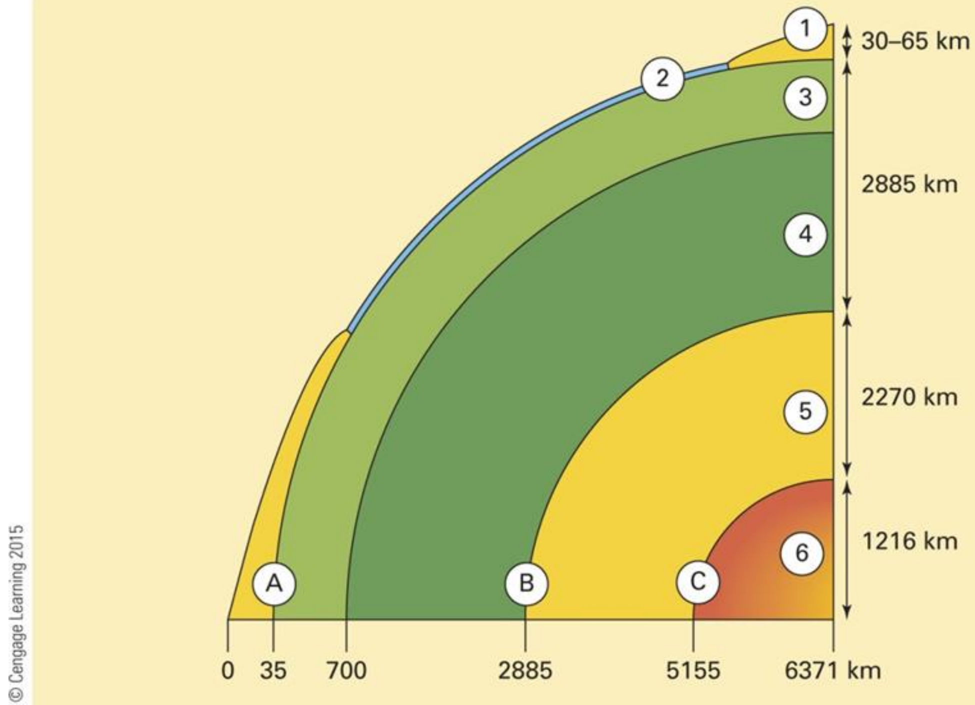


Figure 15.2: Properties of the crust, mantle, and outer and inner cores of the earth. 1. Continental crust; 2. Oceanic crust; 3. Upper Mantle; 4. Lower Mantle; 5. Outer Core; 6. Inner Core; A: Crust/Mantle Discontinuity (Mohorovicic Discontinuity); B: Mantle/Core Discontinuity (Gutenberg Discontinuity); C: Outer Core/Inner Core Discontinuity (Lehmann Discontinuity)

Temperature inside the earth

The interior of the earth is hot. Heat comes from several sources

- primordial heat
- decay of radioactive nuclides
- tidal friction in liquid core

Dominated by radioactive decay of U, Th and K

Distribution of geothermal heat flow

Average heat flow from interior of earth 0.087 W/m^2

Small compared to solar insolation (average 168 W/m^2)

Distribution of geothermal heat flow determined by variations in earth's structure

Regions of high thermal gradient

occur near regions where tectonic plates intersect

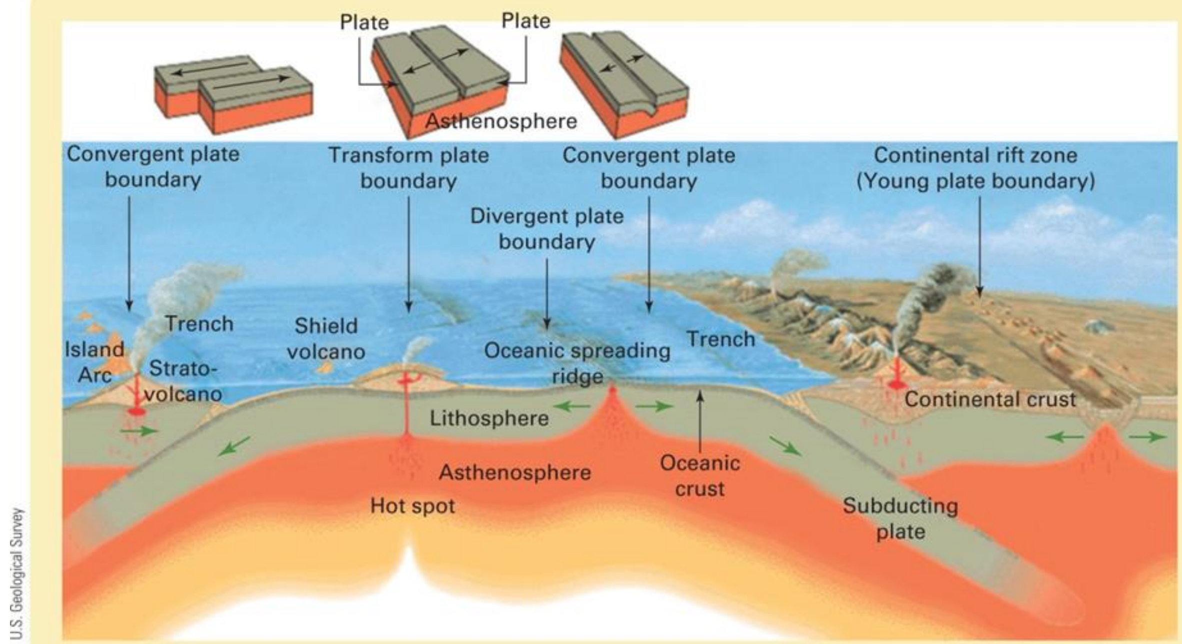


Figure 15.4: Movement of tectonic plates resulting in the formation of hot regions close to the surface of the earth at midoceanic ridges and at continental shelf boundaries.

Classification of geothermal resources

- Normal geothermal gradient (17 - 30 °C/km)
- Hot dry rock
- Hot water reservoirs
- Natural steam reservoirs
- Geopressurized regions
- Magma

Geothermal gradients in the United States

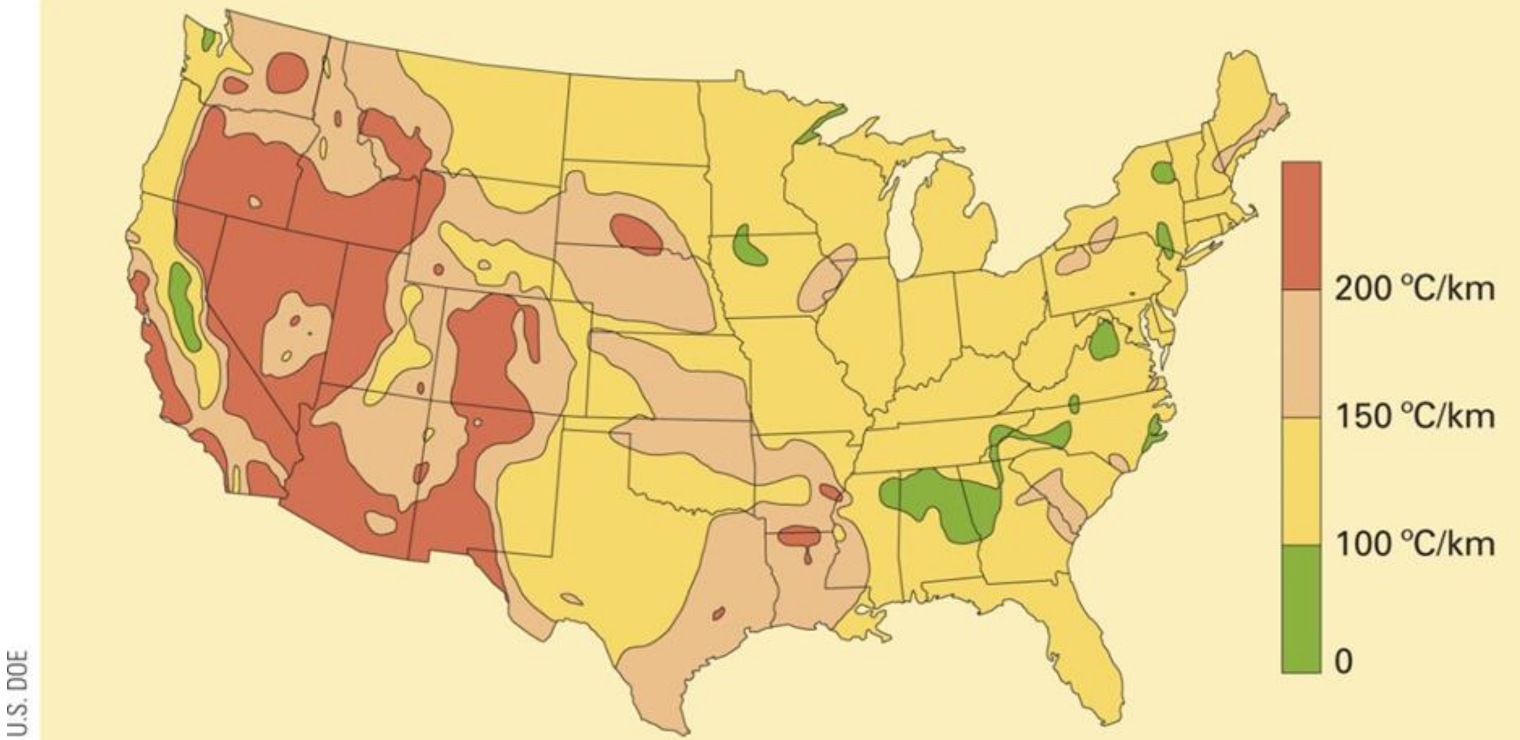


Figure 15.5: Geothermal temperature gradient for the United States in °C/km.

Possible applications of geothermal energy
Normal geothermal gradient

Temperature of about 200°C at a depth of 6 km

Not sufficient to make use of the thermal energy as a method of electricity generation

Most useful for geothermal heat pumps

Hot dry rock

Gradient of > 40°C/km

Well drilled into thermal resource

Hydraulic fracturing used to create reservoir

Working fluid (water) injected to extract heat

Not commercially viable at this time

Hot water reservoirs

Regions of enhanced thermal gradient which naturally contain water

Hot water may be extracted from wells

Hot water may be used for direct heating of electricity generation

In widespread use

Natural steam reservoirs

Reservoirs in regions of enhanced gradient that contain water primarily as steam

Easiest to utilize for electricity generation

Two major deposits: California and Italy

Geopressurized regions

Regions of hot pressurized water containing dissolved methane gas

Mostly in Gulf of Mexico

Can be used as

- source of hot water for heating or electricity generation
- source of methane
- source of pressurized fluid to directly drive turbines to generate electricity

First two have been implemented commercially

Magma

Not sufficiently stable to be used commercially as a source of energy

Direct use of geothermal energy

Distribution of direct geothermal energy use

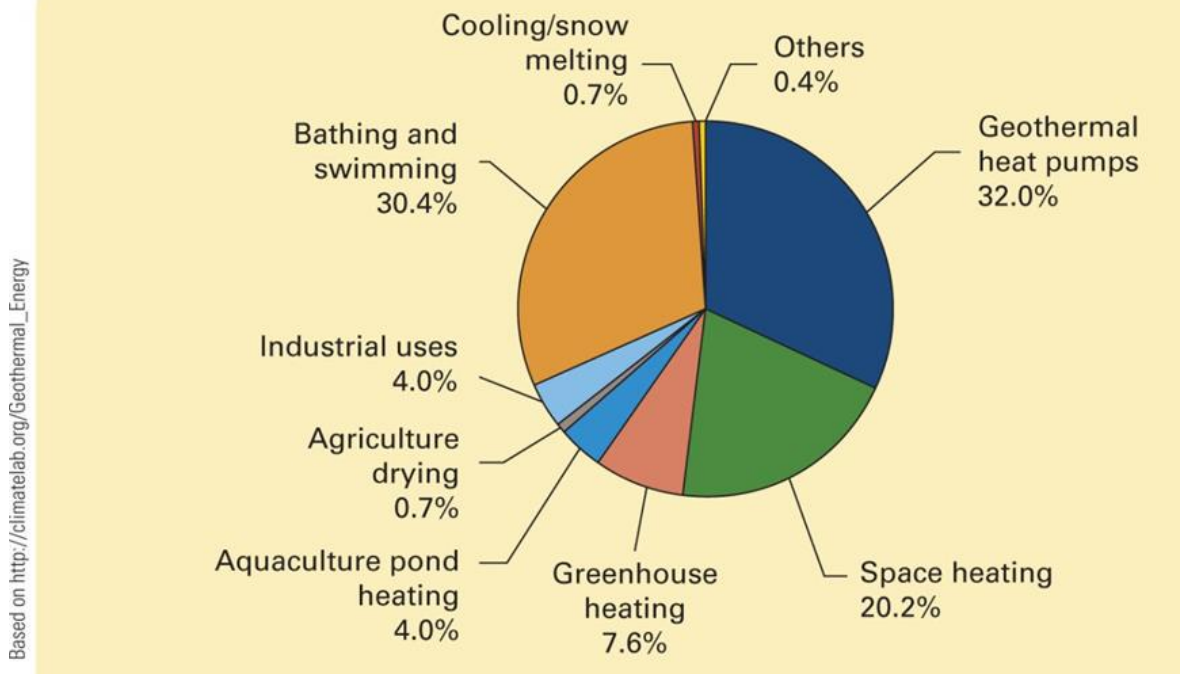


Figure 15.6: Breakdown of the direct use of geothermal energy.

Some examples of direct geothermal heat utilization
Geothermal aquaculture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Alligators raised in a geothermally heated pond in Idaho.

Snow melting

Figure 15.7: Construction of a sidewalk in Reykjavik, Iceland, utilizing heating pipes carrying geothermally heated water to prevent icing.

Geothermal electricity

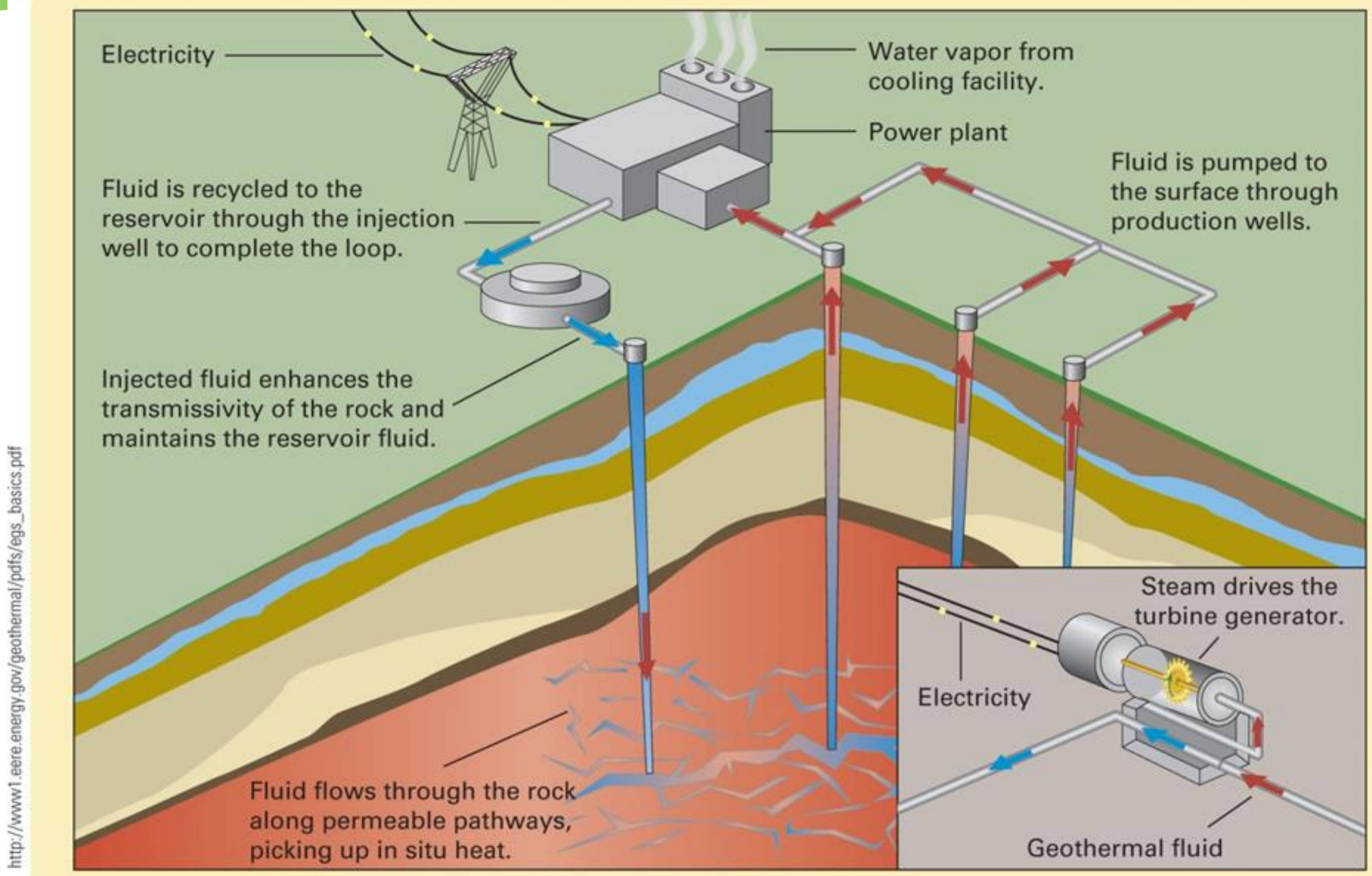

Figure 15.8: General schematic of a geothermal generating station.

Production and injection wells

Hot fluid (water or steam) is extracted through production wells.

After driving turbines it is reinjected through injections wells to maintain reservoir fluid.

Dry steam plants

Steam from geothermal deposit is used to drive turbines

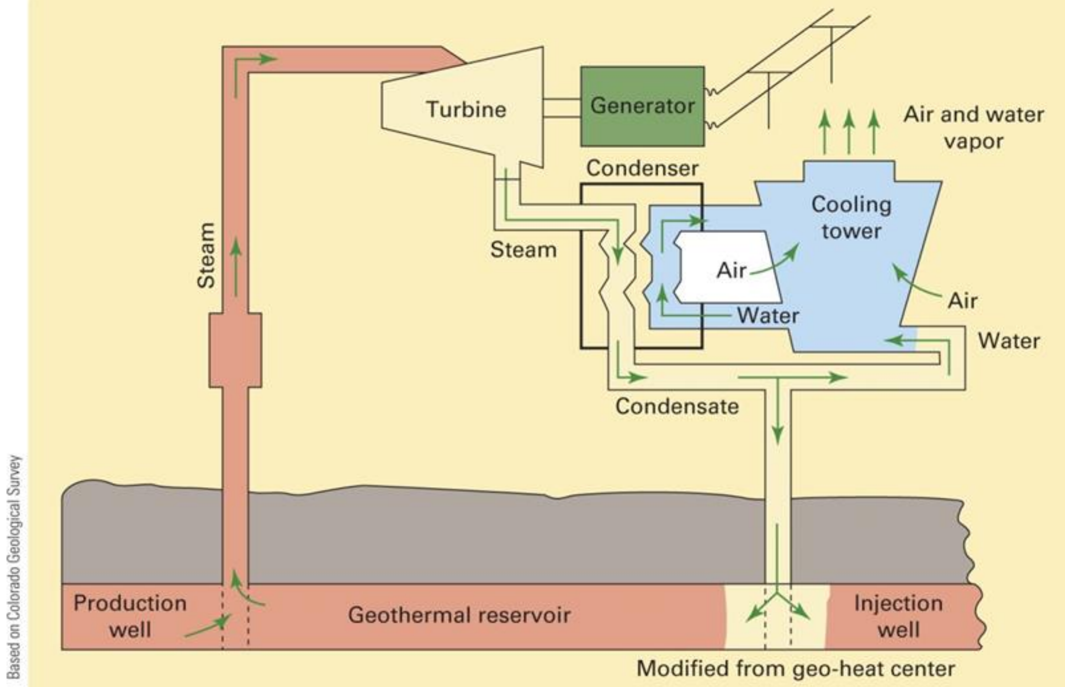

Figure 15.9: Schematic of a dry steam geothermal generating station.

The Geysers in Northern California

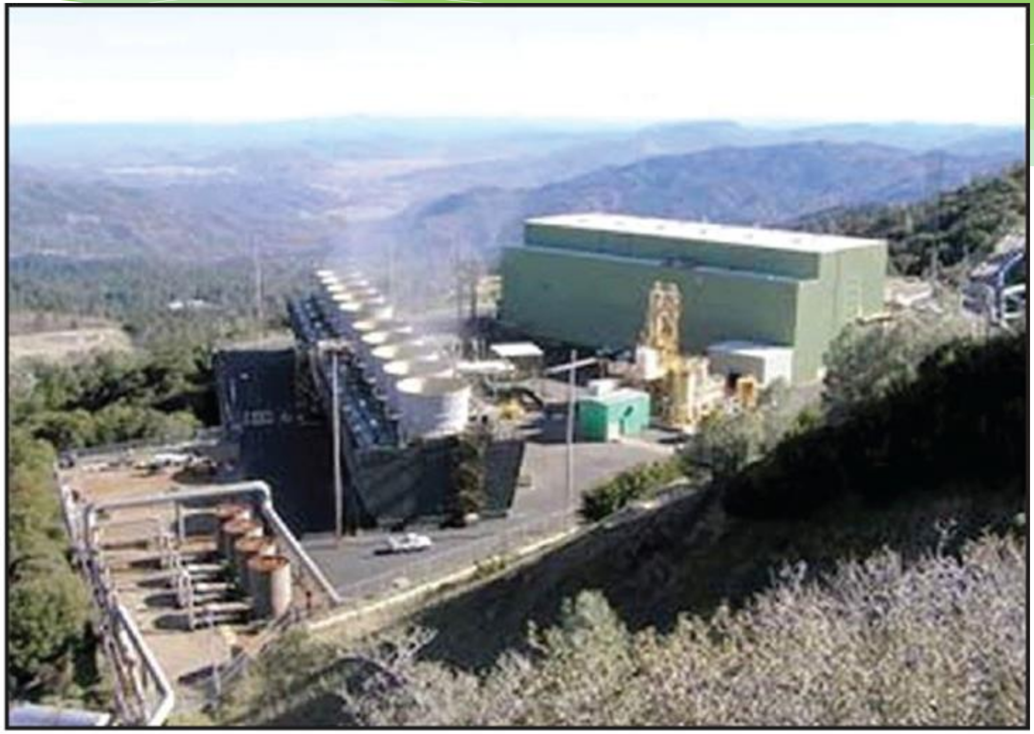

Figure 15.10: A power generating station at The Geysers in California.

typical generating stations are about 50 MW_e

Flash steam plants

Used for deposits of hot pressurized water

Uses steam produced from pressurized hot water by lowering the vapor pressure

Can also be used for direct heating applications

Most common type of geothermal generating station

Schematic of flash steam plant

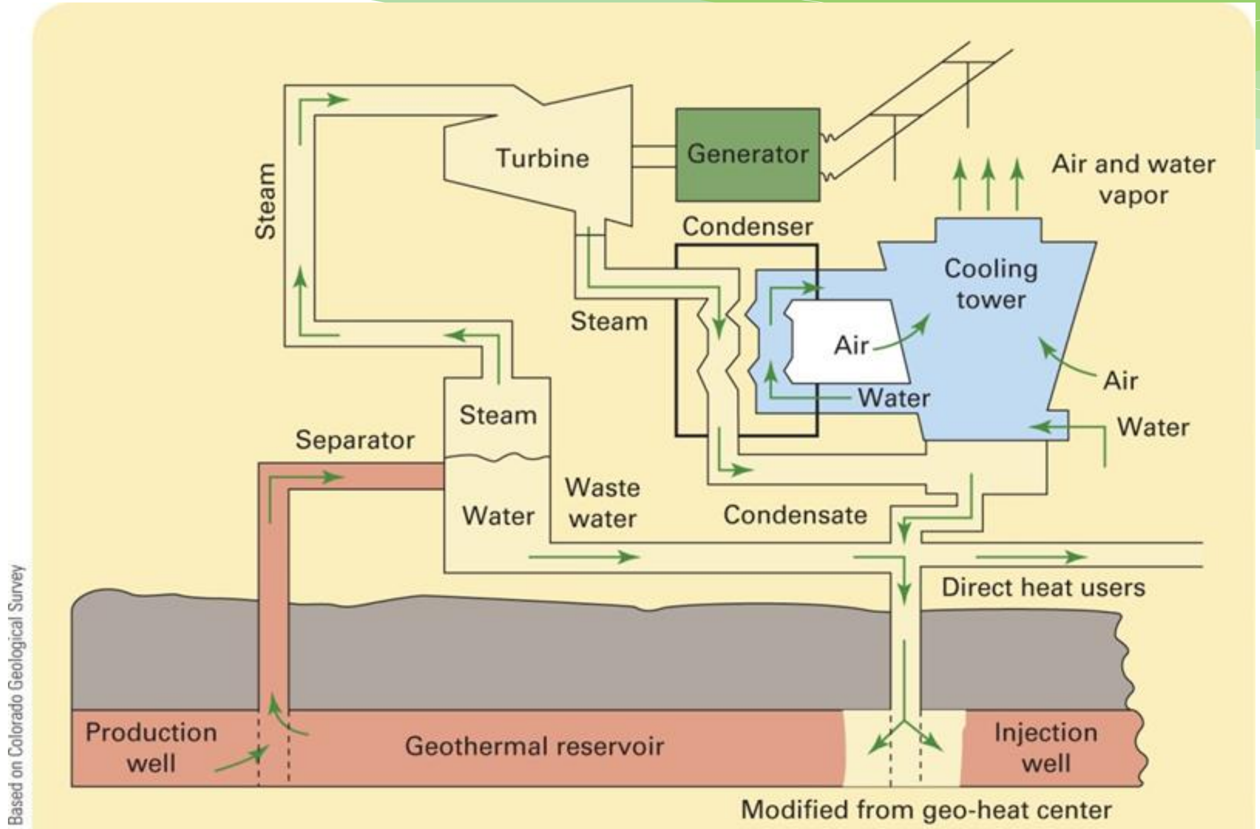

Figure 15.11: Schematic diagram of a flash steam geothermal generating plant.

Flash steam plant in Otake, Japan

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Figure 15.12: Flash steam geothermal power plant in Otake, Japan.

Binary cycle plants

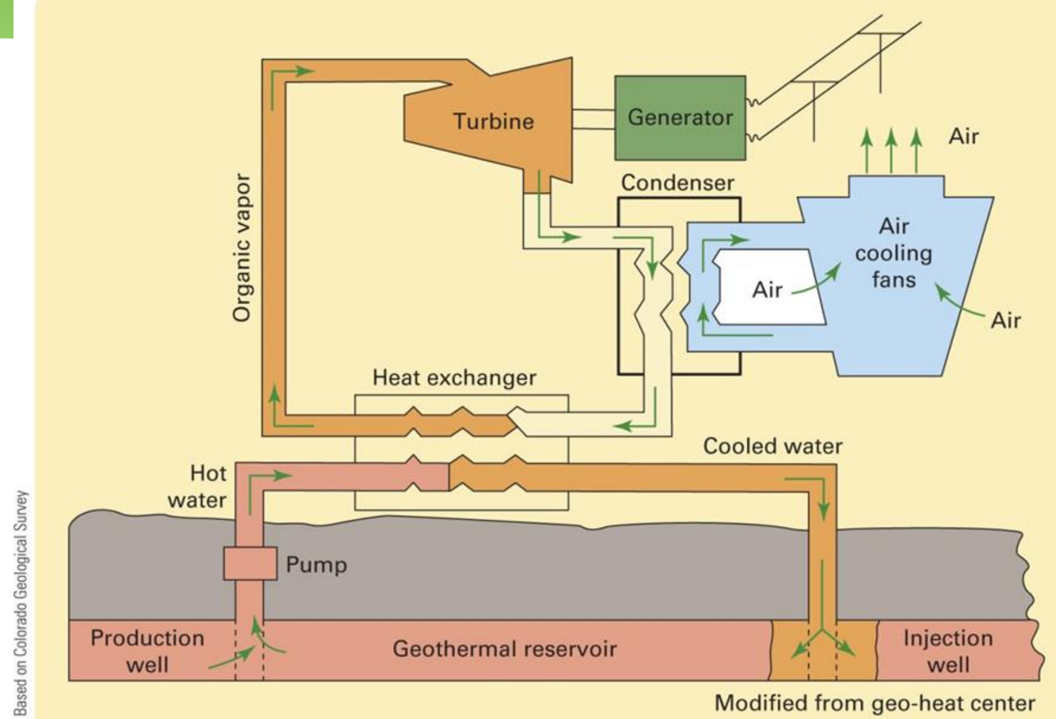

Figure 15.13: Schematic diagram of a binary cycle geothermal generating plant.

Uses hot water or steam to heat another working fluid through a heat exchanger

Binary cycle plant in Nevada

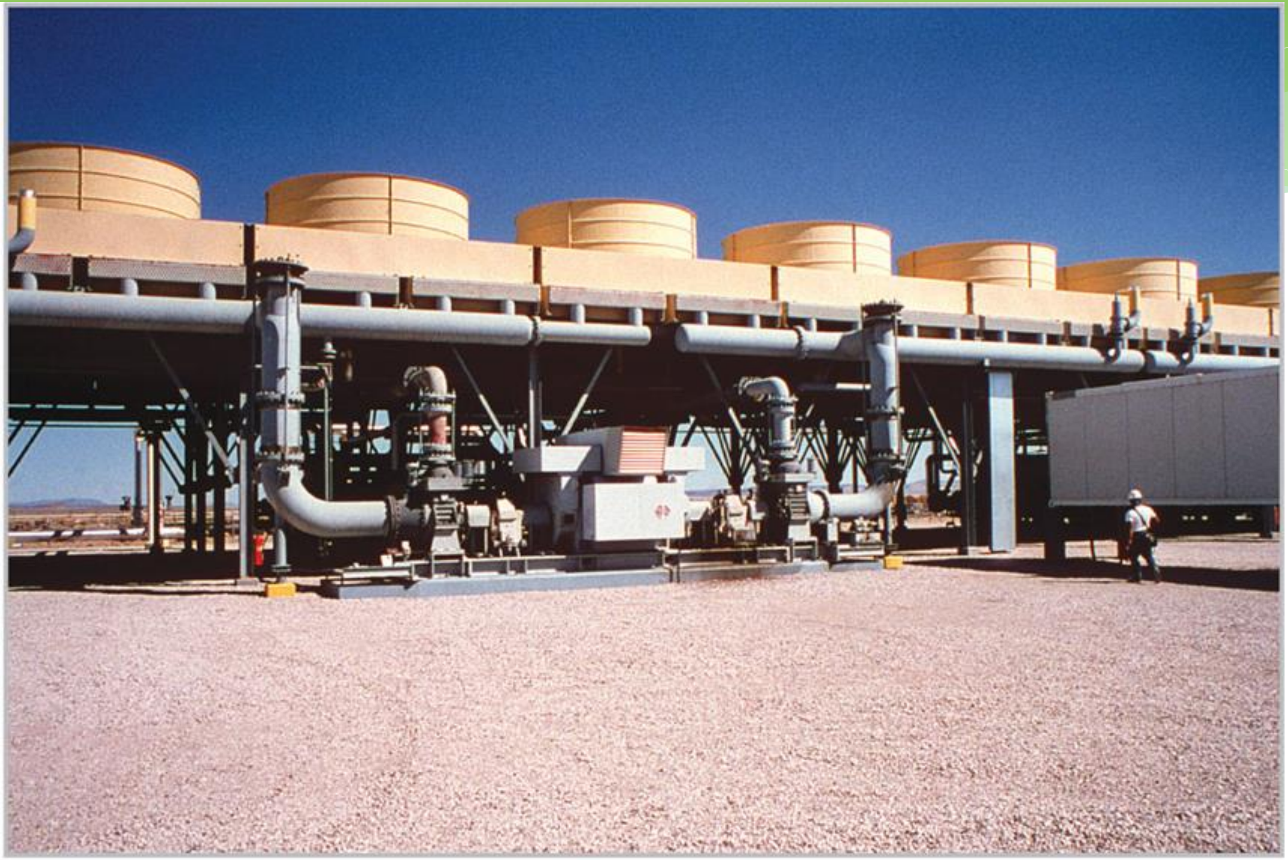

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Figure 15.14: Binary cycle geothermal plant in Soda Lake, Nevada.

World utilization of geothermal energy

Installed capacity for geothermal electricity generation

Table 15.1: Electricity generation from geothermal sources as of 2008 for the world's principal producers and total world capacity.

country	installed capacity (MW_e)
United States	3277
Philippines	1958
Indonesia	1054
Mexico	958
Italy	810
New Zealand	585
Iceland	573
Japan	535
El Salvador	204
Kenya	163
Costa Rica	162
Other	377
world total	**10,656**

Installed capacity for direct use of geothermal energy

Table 15.2: Installed capacity for direct use of geothermal power in 2008.

country	installed capacity (MW)
United States	12,037
China	8898
Sweden	4460
Norway	3300
Japan	2100
Turkey	2084
Iceland	1826
Germany	1640
France	1607
Netherlands	1410
Canada	1126
Austria	1080
Switzerland	1054
other	6888
world total	**49,636**

Based on data from World Energy Council

Distribution of geothermal generating stations

Figure 15.16: Distribution of geothermal electricity generating plants.

Greatest utilization along tectonic plates that border the Asian and North/Central American coasts of the Pacific

Growth of geothermal electricity

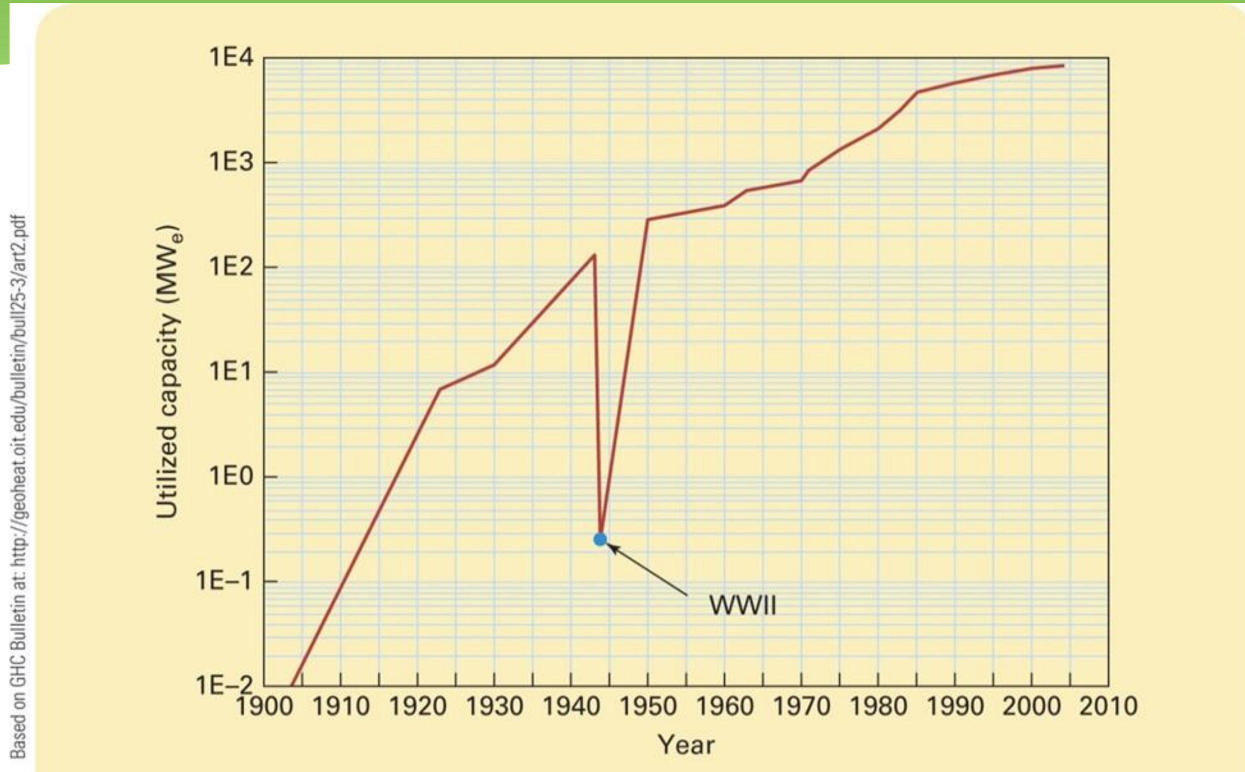

Figure 15.17: World geothermal power production 1904–2004

Substantial increase in use in early part of the 20th century, relatively little growth since about 1980

Advantages of geothermal energy

- Simple well established technology
- Not subject to fluctuations such as wind/solar/tidal/wave energy
- High energy density per unit land area
- Relatively safe with minimal environmental impact

Disadvantages of geothermal energy

- Availability of additional resources is uncertain
- Heat is generally extracted faster than it can be replenished leading to depletion of resource
- Water extracted from underground may contain toxins and needs to be handled carefully
- Reinjection may lead to geological instability (as in the case of fracking)

Summary

- Geothermal energy is associated with the thermal gradient in the earth
- May be used directly for heating or for electricity generation
- Most useful resources in regions of enhanced thermal gradients near tectonic plate boundaries
- Hot water and steam resources most commonly used
- United States is the largest user of both direct geothermal heat and geothermal electricity
- Additional capacity available worldwide may not be great
- Longevity may be uncertain
- Relatively low environmental impact