Sustainable Energy

Lecture 11: Geothermal Energy

Geothermal Resource Types

- Definition – geothermal energy consists of the thermal energy stored in the earth's crust.
- Origins of geothermal energy
  - Upward convection and conduction of heat from the mantle of the earth.
  - Heat generated by decay of radioactive elements in the earth's crust (potassium, uranium and thorium)
  - Intrusions of magma into the earth's crust.
  - Geologic regions associated with tectonic plate boundaries are prime areas of geothermal activity.
- Sources of heat:
  - Hot water
  - Steam (saturated or superheated)
  - Hot rock
- Natural Hydrothermal Systems
  - Systems that produce hot fluid spontaneously.
  - These systems are usually associaqted with zones of recent volcanism and tectonism.

Geothermal Reservoir Systems

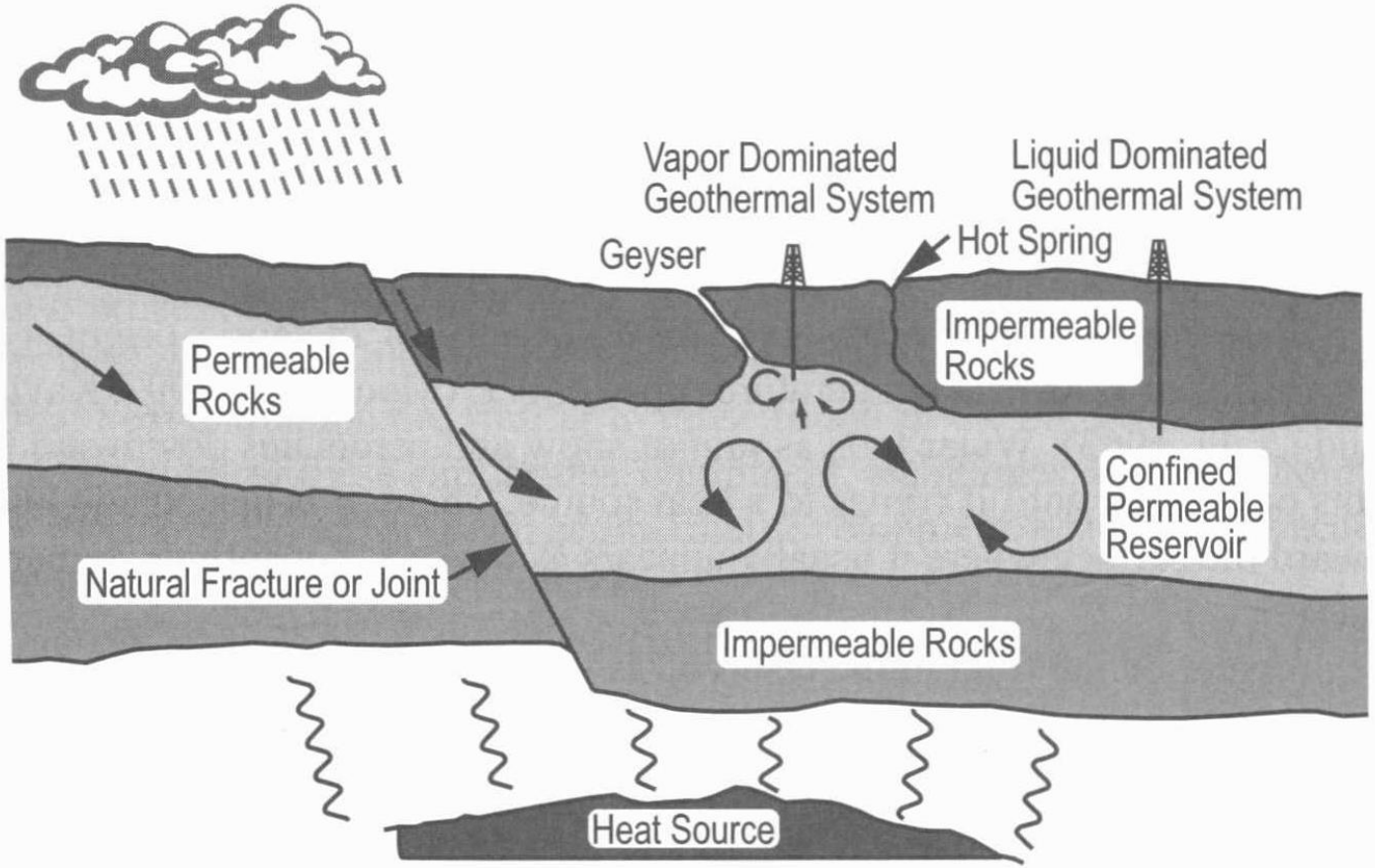


Figure 11.2. Typical features of a natural hydrothermal geothermal reservoir system. Adapted from Mock, Tester, and Wright (1997). Reprinted with permission of *Annual Review of Energy and the Environment*.

Geothermal Sources...continued

- Surface water percolates into the earth through sediments and fissures until it reaches the heat source.
- Once heated it rises to the surface causing geysers, hot springs, fumaroles or solfataras.
- Some hydrothermal systems produce steam and are called, "vapor-dominated" systems. This happens in underground reservoirs where the fluid is pressurized to prevent boiling. Steam forms in the upper portion of the reservoir.

- **Geopressured Systems**
  - Fluids contained in sandstone-shale layers are often overpressured by up to 600bar (600 atm) at temperatures of 150-180 degrees C.
  - Geopressured reservoirs usually contain methane in solution.
  - Salinity levels can effect the utilization of some reservoirs.
- **Hot Dry Rock (HDR)**
  - Sometimes the low formation permeability or absence of fluid of rock in a reservoir prevents direct utilization.
  - These systems are called enhanced geothermal systems (EGS) by the US DOE.
  - HDR systems are theoretically available everywhere on earth.
  - You just have to drill deep enough to find heat >150 degrees C for electricity production and >50-100 C for direct heat use.

HDR Technology

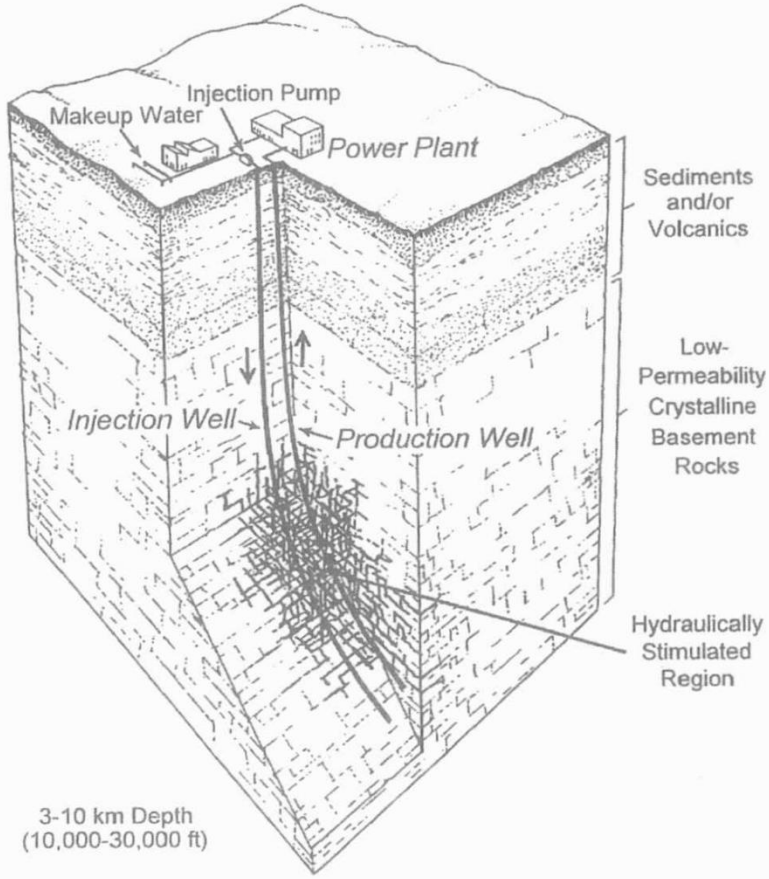


Figure 11.3. Hot dry rock reservoir concept for low-permeability formations. Source: Mock et al. (1997). Reprinted with permission of *Annual Review of Energy and the Environment*.

Geothermal sources…continued

- Magma – rock that is partially or completely molten (650-1000 degrees C).
  - It is a challenge for currently technology to harness this potentially efficient source of heat for electric generation.
- Ultra low-grade systems
  - Geothermal heat pumps (GHPs) operate at shallow depths (2-4m) where the earth's temperature is relatively constant. The primary use is in home or agricultural settings.
  - Geothermal wells can also be drilled to increase the efficiency of the GHPs system. These are gaining popularity in heating commercial/industrial buildings.
  - The typical coefficient of performance (COP) of a typical GHP is about 4 or more (4 units of thermal energy are transferred for every 1 unit of electrical work done on the system).
- **Markets for geothermal energy**
  - Geothermal power plants have smaller capacities (50-100MW) than nuclear and fossil fuel plants.
  - The US total generating capacity is 600,000 MWe; in 2000 only 2500 MWe was supplied by geothermal energy.
  - Low-grade GHP use in residential and commercial buildings has expanded exponentially since the 1990s.

Geothermal Resource Size and Distribution

- Table 11.1 shows that the resource base for geothermal energy is incredibly large…..if partially developed it could easily provide all of our electricity needs now and into the future.
- We need more research and development funds to increase the fraction of the resource base that can be produced.
- Geothermal energy is the second leading source of renewable energy today. The potential for resource development is great and we should see more interest in this readily available source of energy.

Worldwide Geothermal Resources

Table 11.1. Geothermal Worldwide Resource Base Estimates—Total Thermal Energy Content in Place (Q)

	Total Q in 10^3 quads[1]	
Resource Type	**US**	**World**
Hydrothermal (vapor and liquid dominated)	9.6	130
Geopressured[4]	170	540
Magma[3]	500 – 1,000	5,000
Hot Dry Rock[2]	30,000	105,000
Moderate to high-grade ($\nabla T > 40°C/km$)	6,000	26,500
Low-grade ($\nabla T \leq 40°C/km$)	24,000	78,500

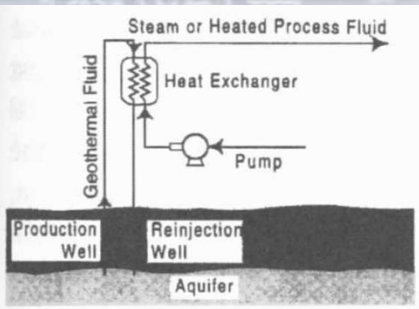
1. Q = 1 quad ≡ 10^{15} BTU ≈ 10^{18}J with
   2003 worldwide commercial energy demand = 400 quads and
   2003 US commercial energy demand = 100 quads
2. includes hydraulic and methane energy content
3. to depths of 10 km and initial rock temperatures >650°C
4. to depths of 10 km and initial rock temperatures >85°C

Sources: Mock et al. (1997), Armstead (1983), Armstead and Tester (1987), Duchane (1994), and Rowley (1982); US figures based in part on USGS estimates (Muffler and Guffanti (1978), Sass (1996) and Sass et al. (1993)).

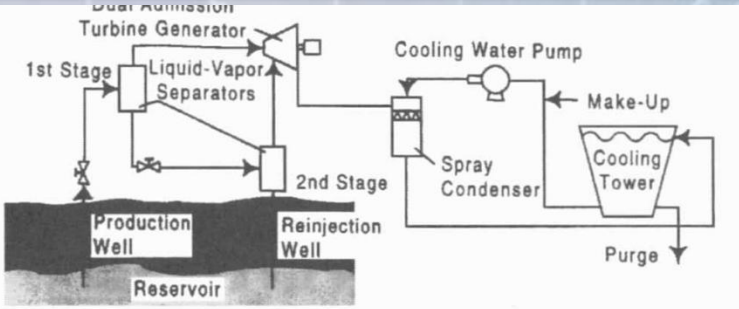
Energy Recovery Technologies

- Drilling and completing wells for geothermal energy involve methods similar for oil or gas wells.
- For depths between 1 and 5 km, geothermal wells are 2-4 times as expensive than oil or gas wells. Costs go up exponentially the deeper one drills (see Figure 11.6).
- Types of Energy Recovery Technologies (see Figure 11.10):
  - Non-electric, direct heat utilization
    - Direct thermal utilization using a heat exchanger.
    - Geothermal (groundwater) heat pump
    - Geothermal (groundsource) heat pump
  - Electric Power Generation
    - Rankine cycle
      - Direct steam
      - Binary Fluid cycle (uses a heat exchanger)
      - Two-stage flash cycle (two pressure reductions that produce steam from pressurized hot water)
    - Efficiencies for geothermal plants are much lower (5-20%) versus 35-60% for fossil fuel or nuclear plants.

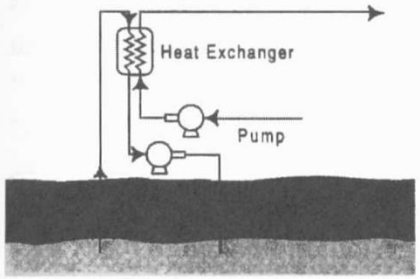
Geothermal Technologies



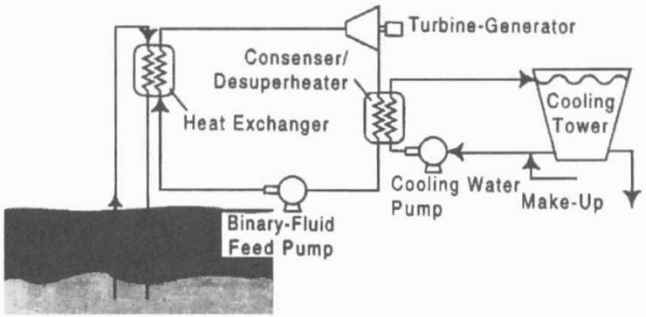
(2.a) Direct Thermal Utilization



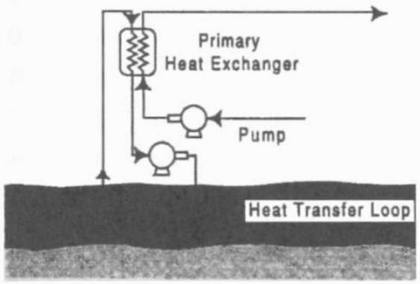
(2.d) Two-Stage Flash Cycle



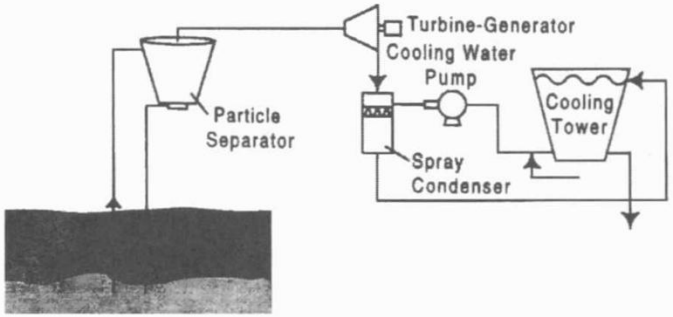
(2.b) Geothermal (Groundwater) Heat Pump



(2.e) Binary Fluid Cycle



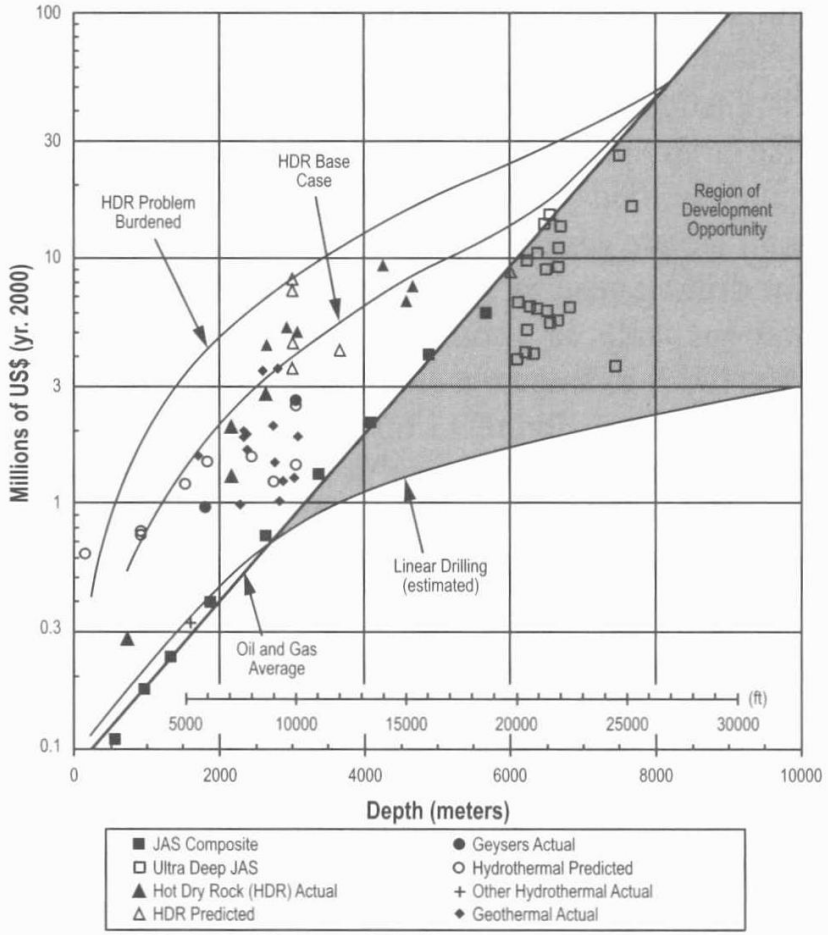
(2.c) Geothermal (Groundsource) Heat Pump



(2.f) Direct Steam Cycle

Figure 11.10. Energy utilization options for geothermal resources. Adapted from Mock et al. (1997). Reprinted with permission of *Annual Review of Energy and the Environment*.

Geothermal Drilling Costs



1. JAS = Joint Association Survey on Drilling Costs.
2. Well costs updated to US$ (yr. 2000) using index made from 3-year moving average for each depth interval listed in JAS (1976–2000) for onshore, completed US oil and gas wells. A 17% inflation rate was assumed for years pre-1976.
3. Ultra deep well data points for depth greater than 6 km are either individual wells or averages from a small number of wells listed in JAS (1994–2000).
4. "Geothermal Actual" data include some non-US wells (Mansure, 2004).

Figure 11.6. Drilling costs for completed wells showing the effect of advanced linear drilling technology. Updated by Augustine, personal communication (2004).

Sustainability Attributes

- Environmental impacts of geothermal
  - Land and water use
  - Noise
  - Seismic and subsidence risks
  - Gaseous emissions
  - Liquid effluents
  - Solid waste from development, production, decomissioning of the field.
- Many existing geothermal plants are nearly emissions and waste-free and have a small footprint on the earth.
- Geothermal electricity can be used baseload and peaking needs.
- Geothermal power plants components use currently available technologies that are readily available and modular.
- Geothermal energy can reduce our carbon footprint and listed pollutant emissions.
- Geothermal might be used to produce hydrogen fuel for transportation.

Geothermal Energy Today/Status Report

- Geothermal generating capacity has been exponentially increasing at about 8.5% per year since 1920 (see Table 11.14).
- The most rapid development for electrical power generation has been in the Pacific Rim countries (Philippines and Indonesia).
- We currently have about 2800 MW of geothermal generating capacity in the US…..serves about 3 million people.
- 7% of California's electricity and 25% of Hawaii's electricity comes from geothermal generation.
- The USGS has estimated that the northern Gulf of Mexico basin contains about 170,000 Quads of energy (107,000 quads hydrothermal and 63,000 quads dissolved natural gas).
- There exists an enormous reservoir of energy in HDR systems but as of yet no commercial operations have been tested.
- Geothermal energy costs can complete with fossil fuel and nuclear energy in the current market (see Table 11.3).

Geothermal Generating Capacity

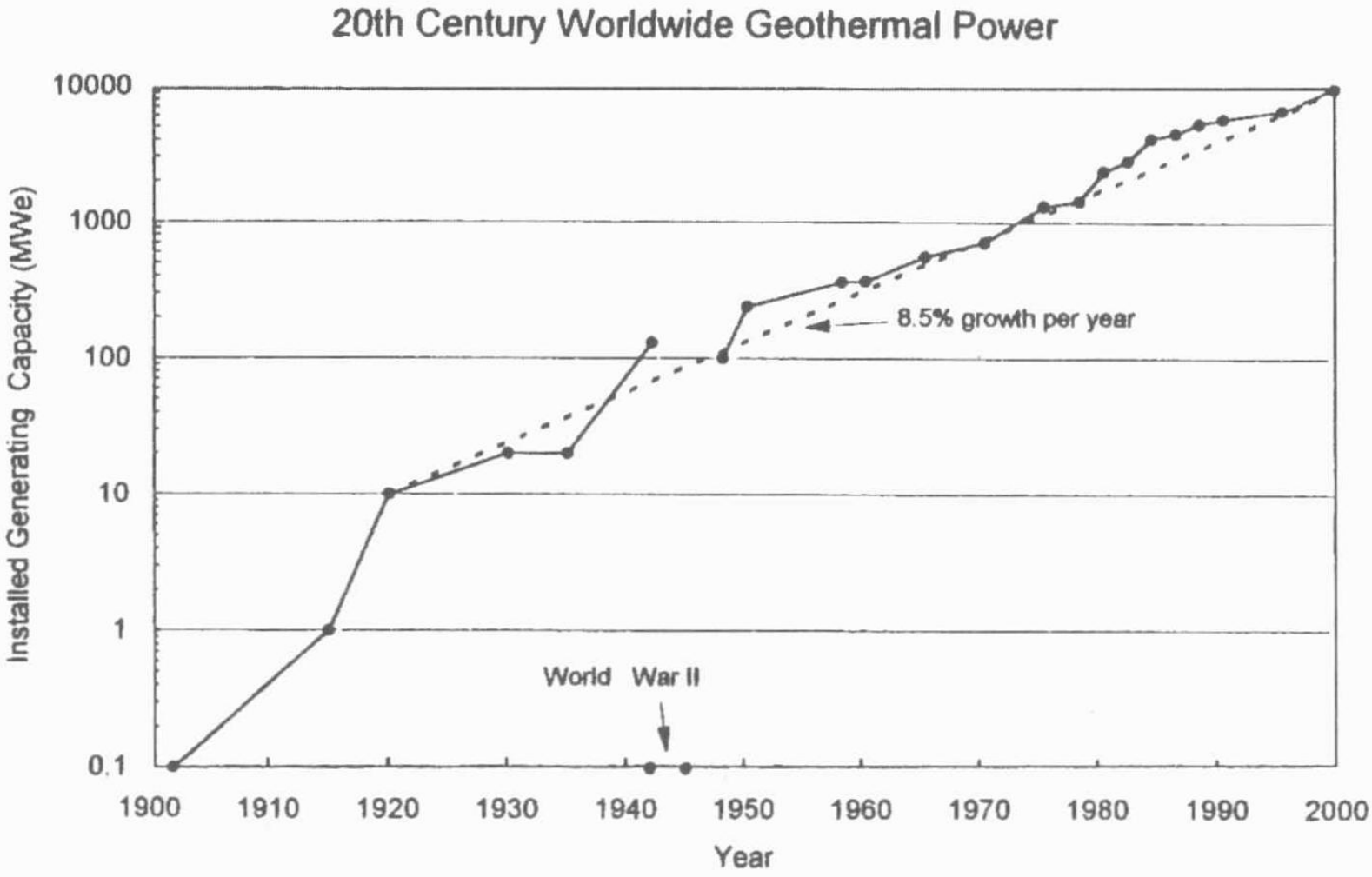


Figure 11.14. Worldwide geothermal electric power generating capacity. Updated from Mock et al. (1997). Reprinted with permission of *Annual Review of Energy and the Environment*.

HDR Geothermal Electricity Costs

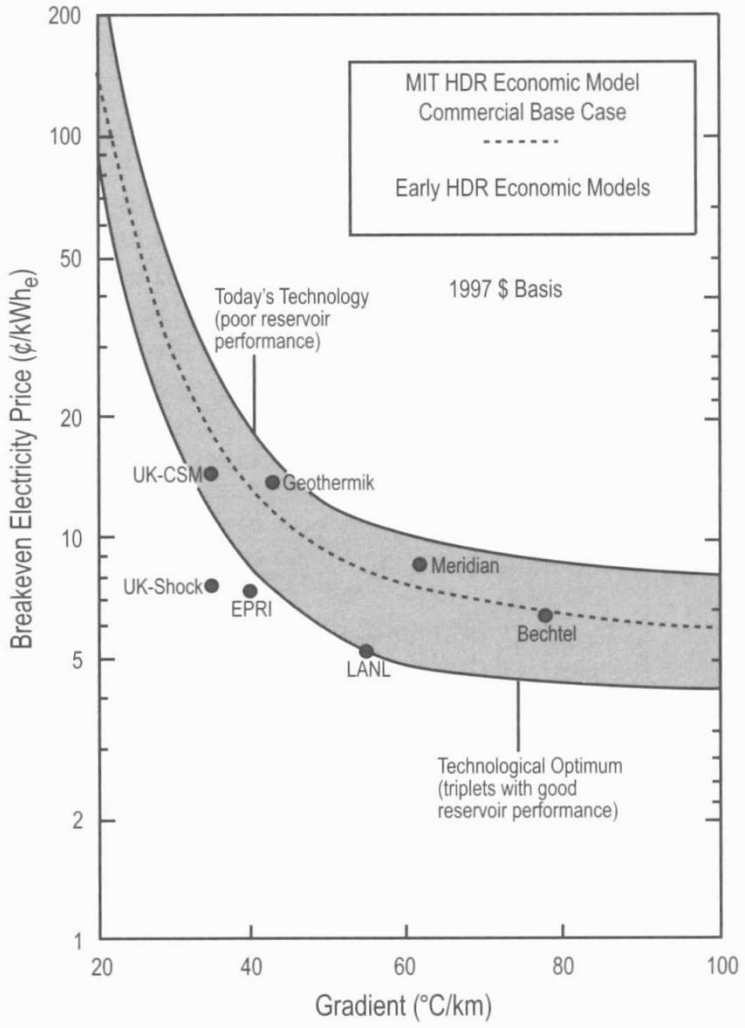


Figure 11.16. Estimated breakeven busbar electricity prices as a function of the geothermal gradient for HDR/EGS systems (updated from Tester and Herzog (1990)).