Lecture# 18
Geothermal Energy

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April 8, 2020

Material in this lecture is based on Prof J Tester's (previously at MIT and currently at Cornell) lecture on the same subject.

Geothermal energy resources

- Hydrothermal: liquid and superheated water
- Hydrothermal: Vapor and dry steam
- Geopressure: methane, hydraulic and thermal energy
- Magna: Hot dry rock or Enhance Geothermal Systems

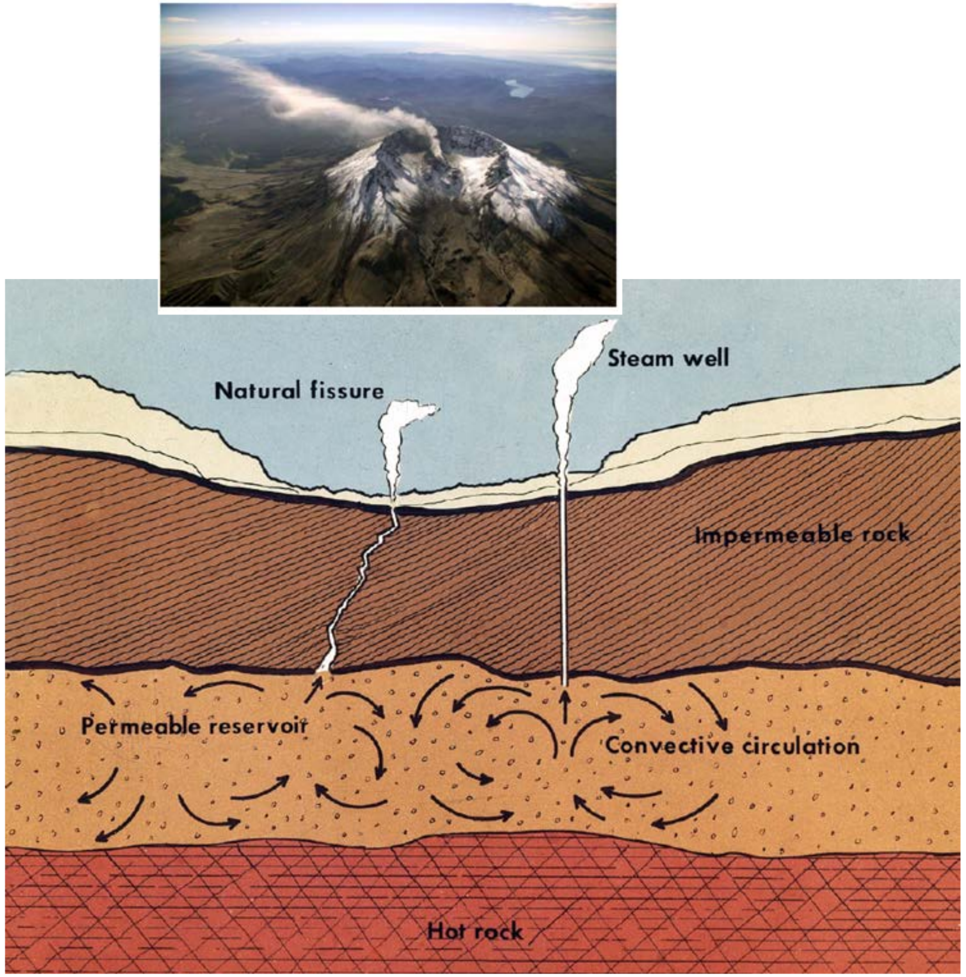
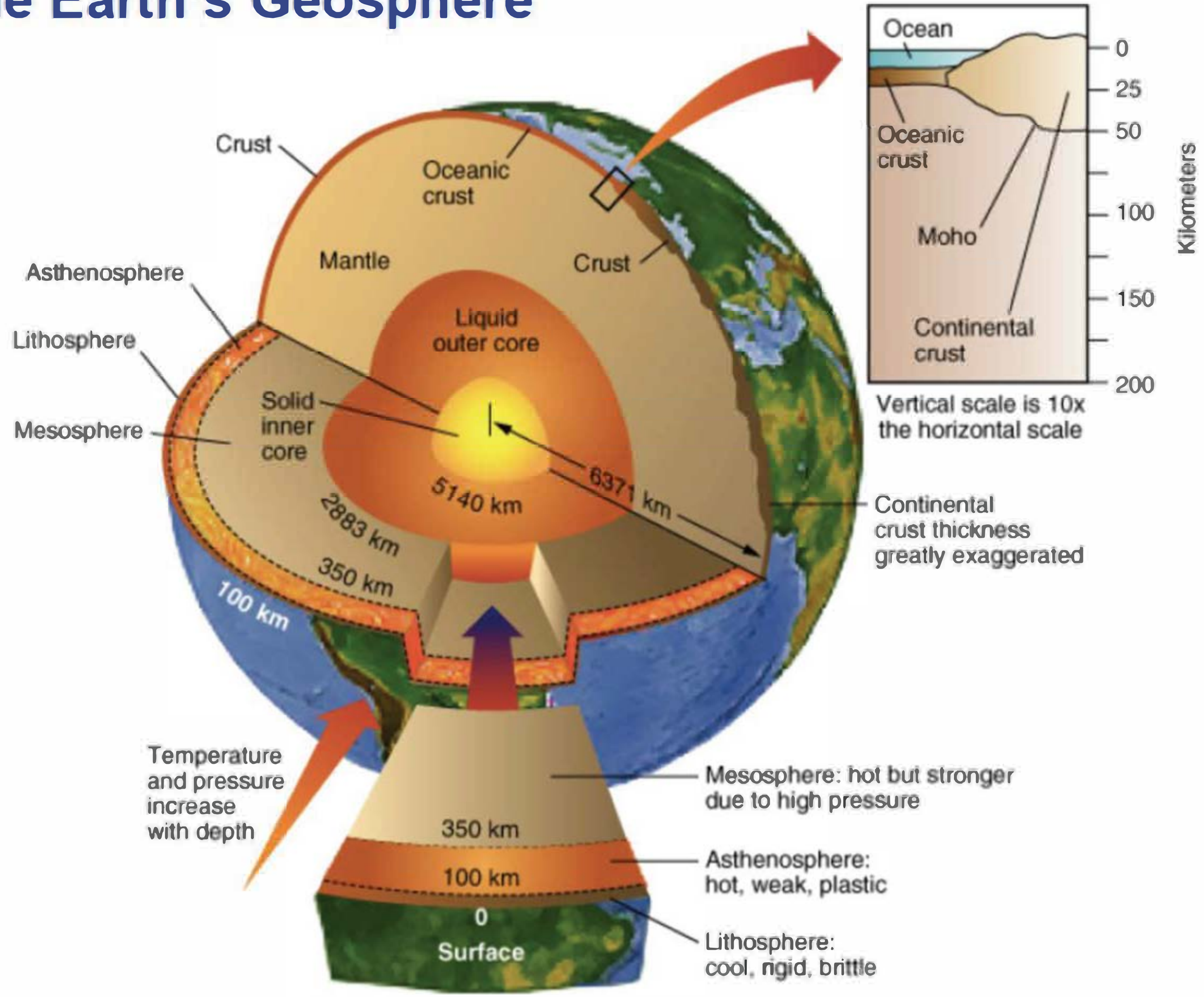


Image courtesy of Idaho National Laboratory.

Looking to "inner space" for opportunities in the Earth's Geosphere



Geothermal energy:

- Renewable, non depleteable on a short time scale (renewal time ~ 2-3 time depletion time
- Reasonably well distributed: available everywhere at 6 km depth, and at shallower depths (3-6 km) in “high-grade” regions
- Provides low grade heat, 100-200 C.
- Scalable: 5-50 MW modules
- Dispatchable: high capacity factor (90%) suitable for base load, no need for storage
- Clean energy, low emission, low footprint
- Uses of-the-shelve power plant equipment
- Cost competitive especially for high grade hydrothermal systems
- BUT EGS require deep drilling

Classification of geothermal resources and reserves

Note that 40 C/km is high quality geothermal energy!

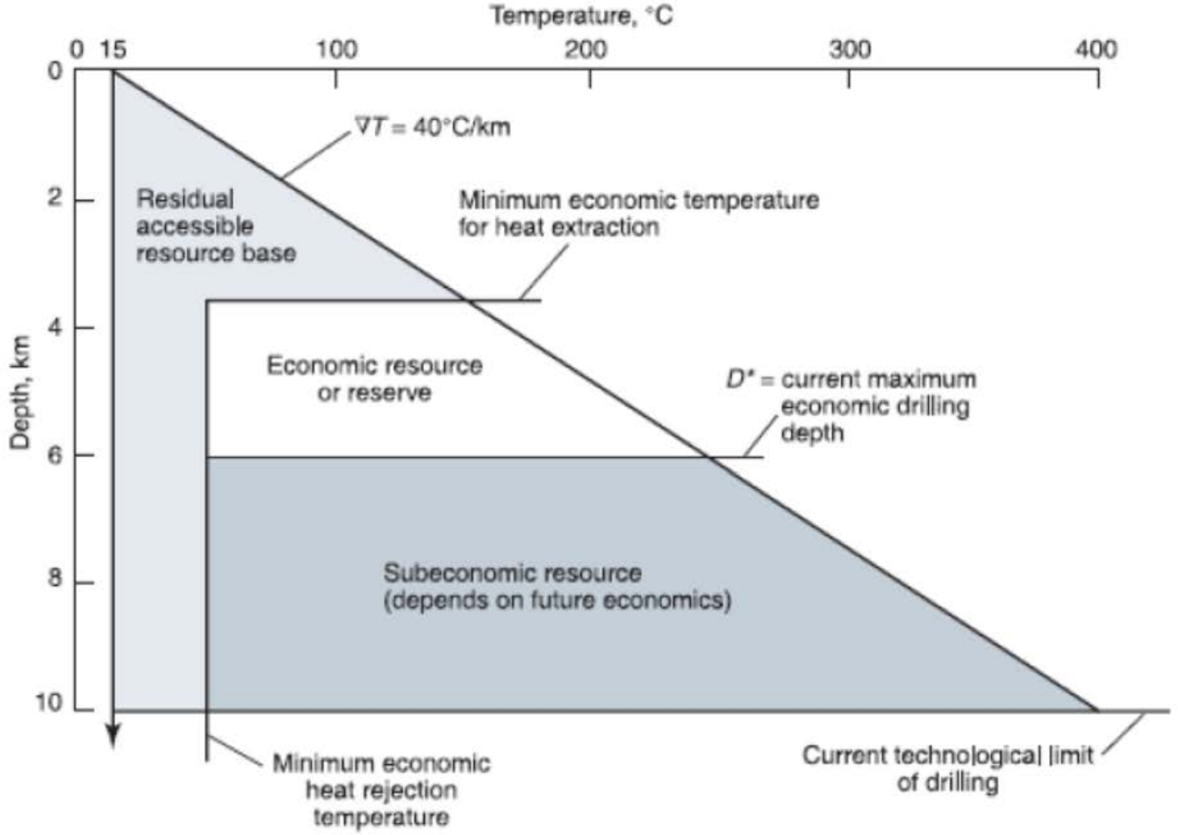
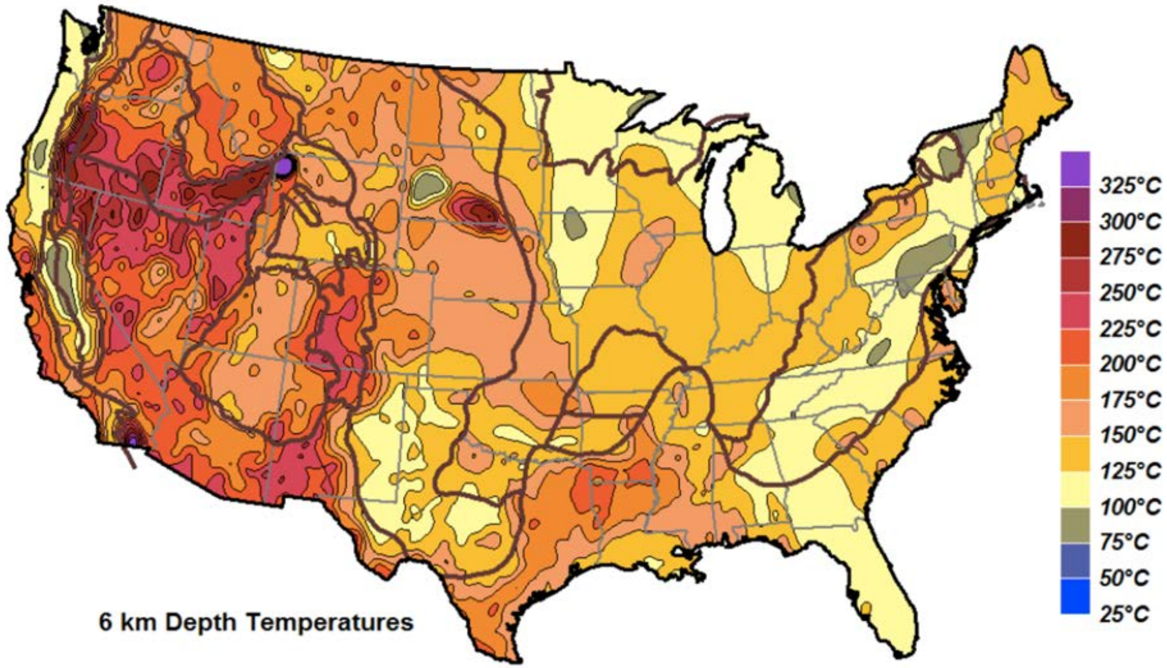
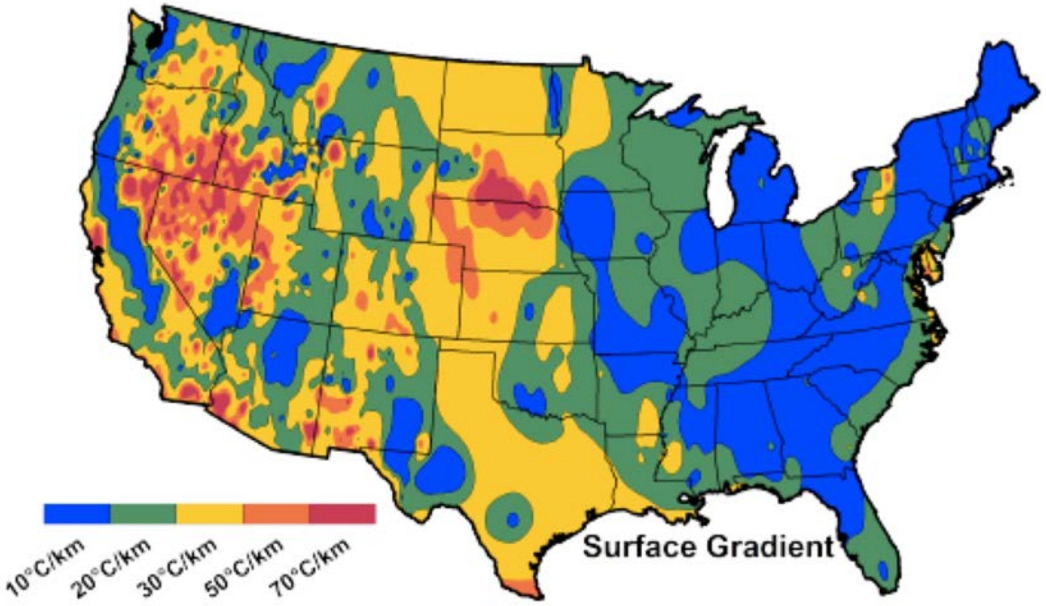


Figure 11.4. Idealized depth versus temperature profile for a hypothetical 40°C/km geothermal resource. The resource base and economic resource or reserve regions are shaded in different tones to illustrate the factors limiting the portion of the total resource base that can be economically produced with a specified set of technologies and economic factors. Adapted from Tester and Grigsby (1980). Reprinted with permission of John Wiley & Sons.

The temperature gradient is the most critical factor!



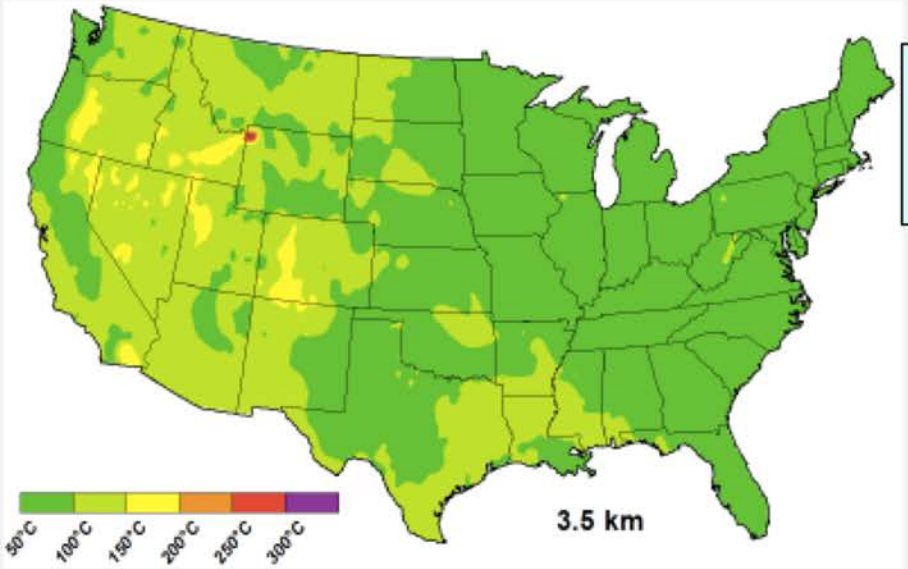
From Blackwell and Richards (June, 2007)

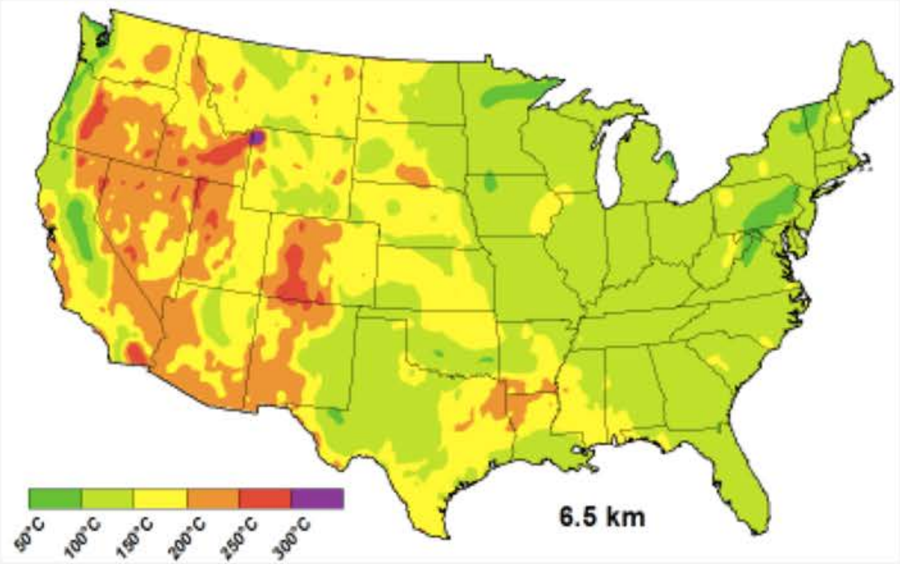


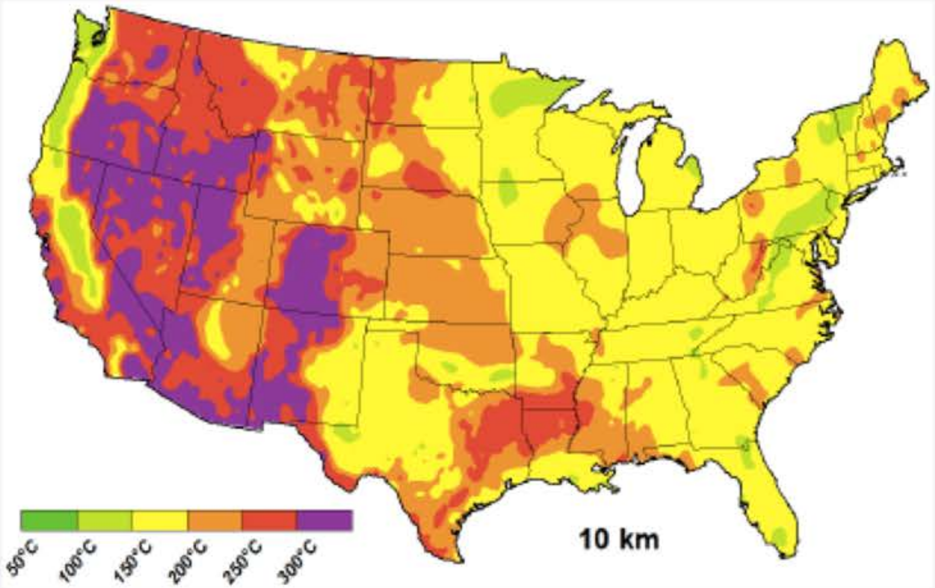
Average surface geothermal gradient
from Blackwell and Richards, SMU (2006)

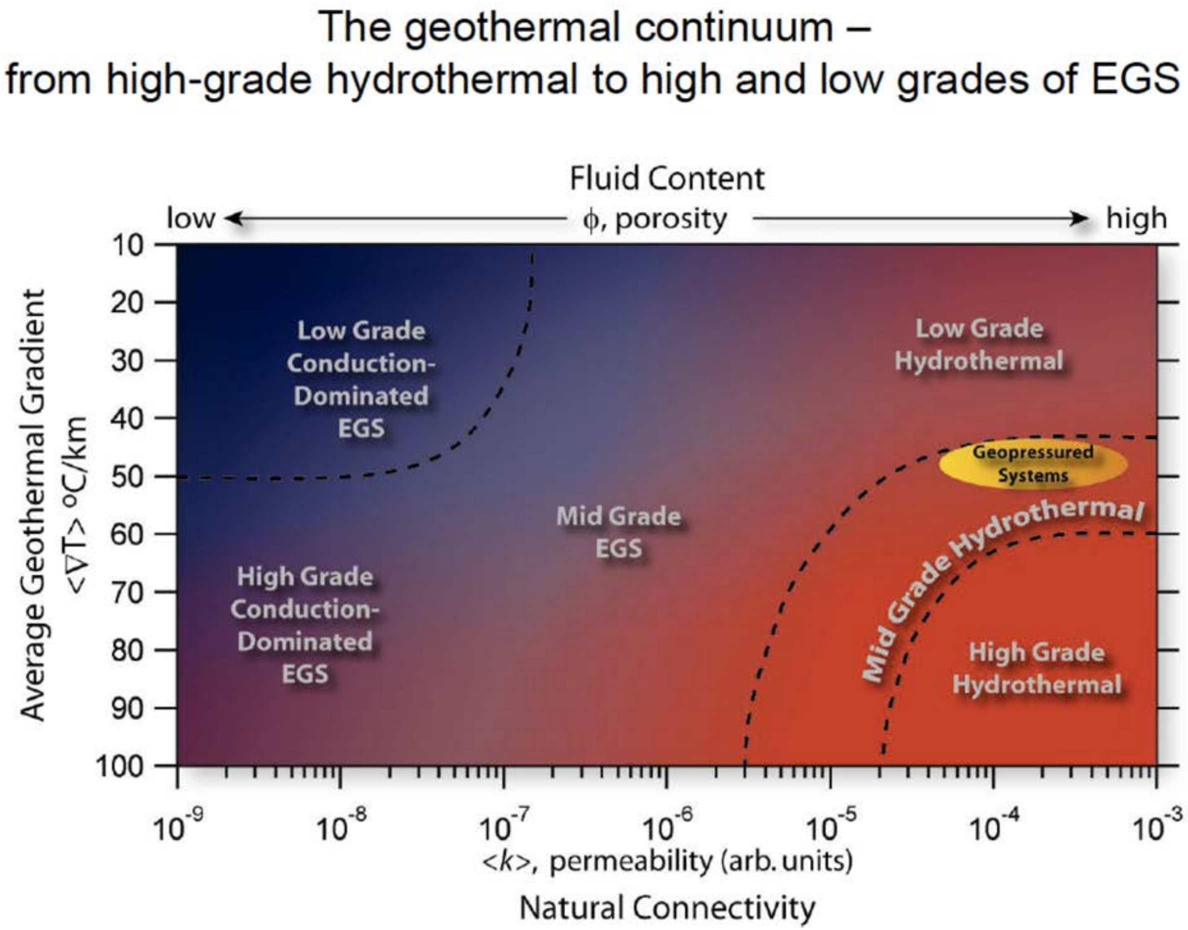
6 km is the limit of economic drilling, mostly used for oil and gas

Estimated Temperatures at Specific Depths

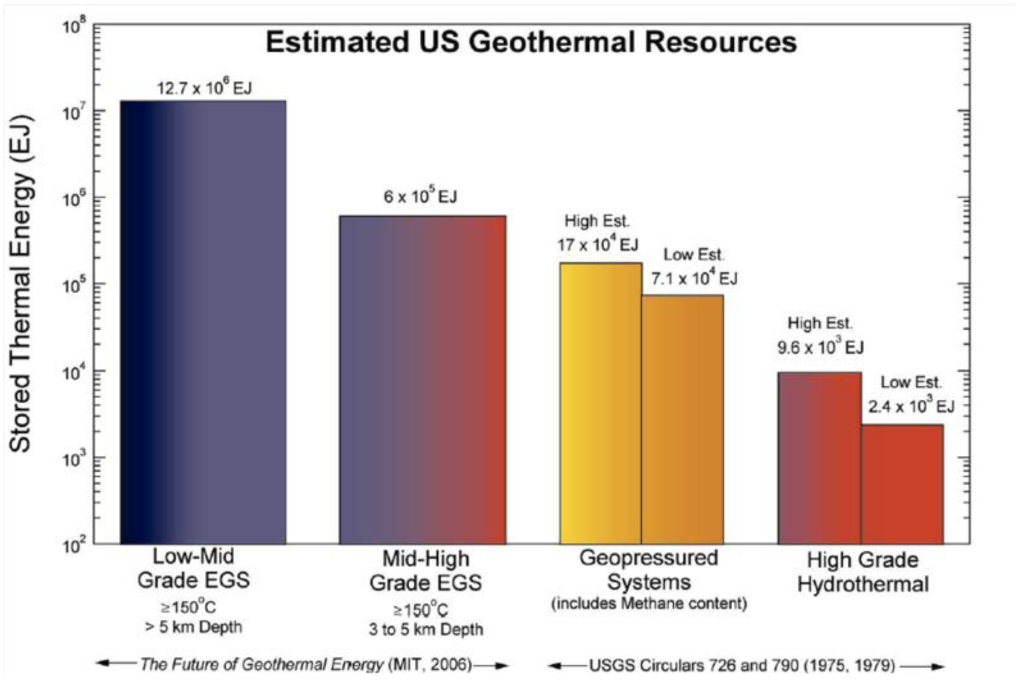








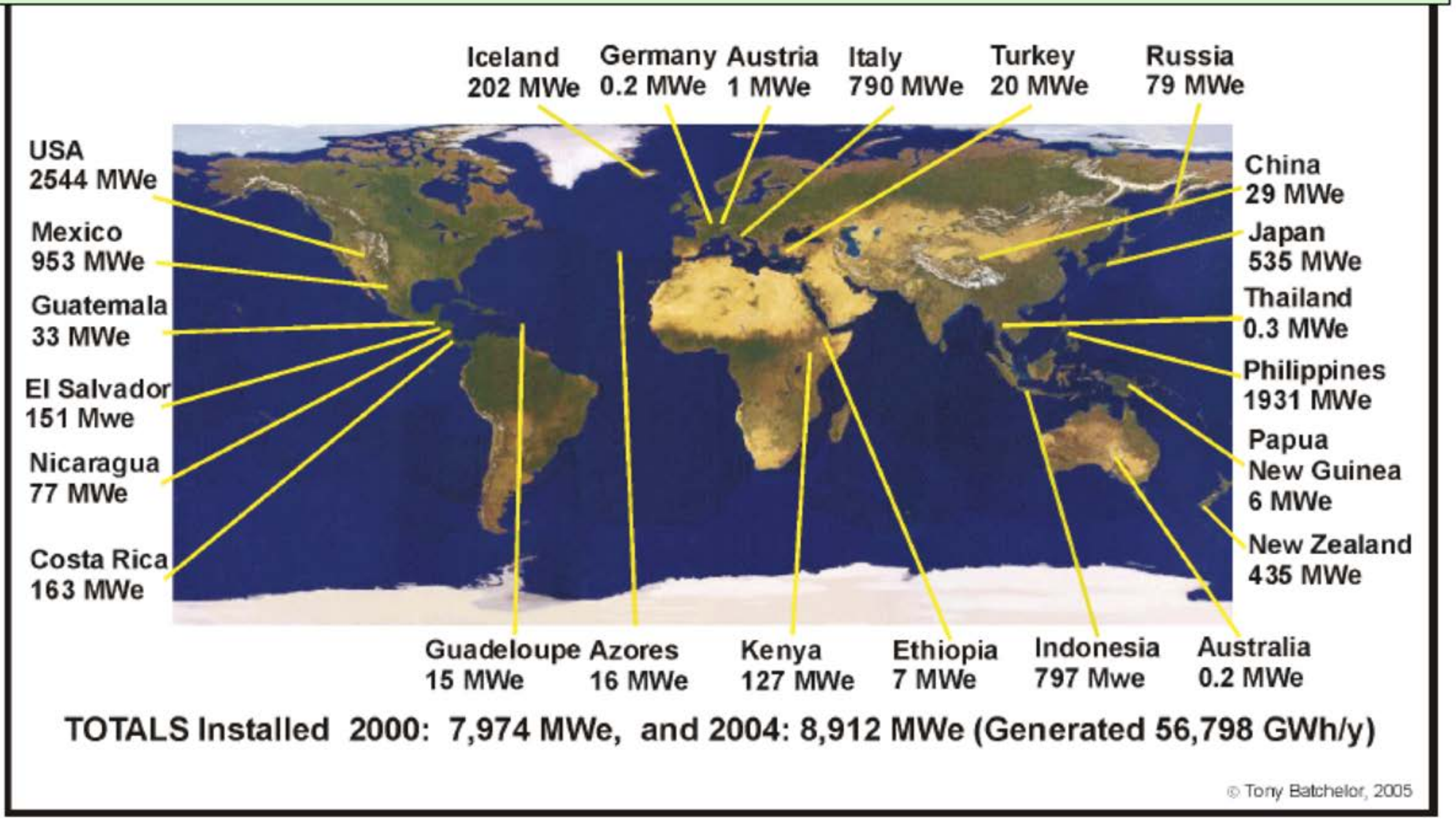
US Annual use ~ 100 EJ



Figures courtesy of Hildigunnur Thorsteinssona, Chad Augustinea, Brian J. Andersonb, Michal C. Moorec, and Jefferson W. Tester. Used with permission.

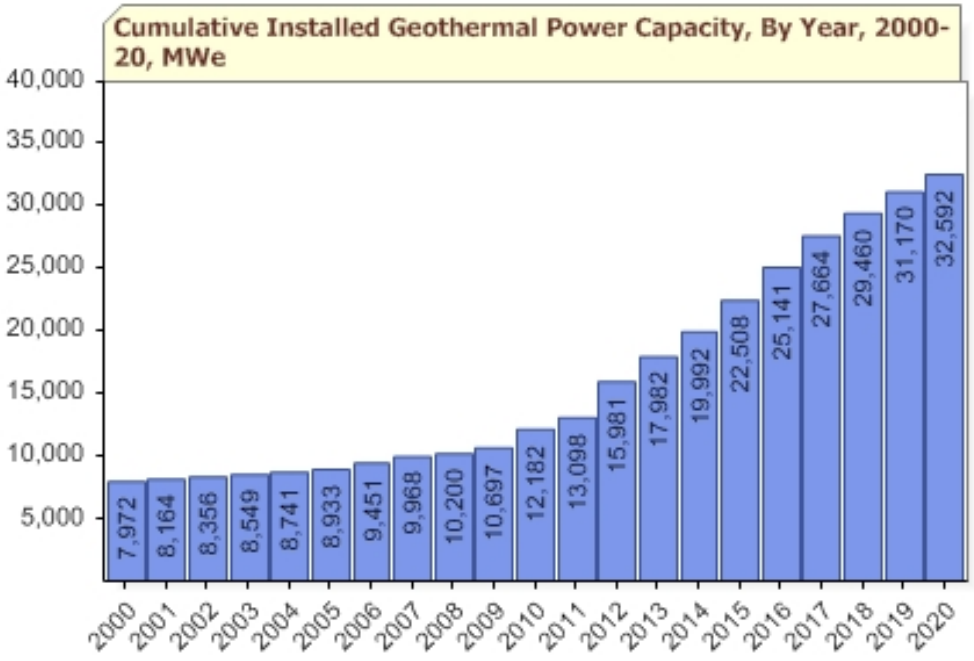
- Hydrothermal resources depend on high permeability to naturally bring hot water and steam to the well. Water comes up under its own pressure.
- EGS: Enhanced Geothermal Systems, futuristic systems that rely on heat conduction to heat up a fractured well where water is injected to recover the heat and brings it to the surface.

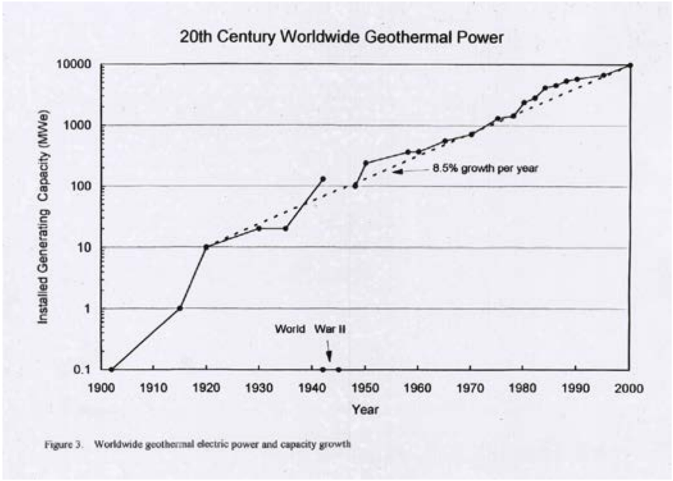
Today there are over 10,000 MWe on-line or under construction
Iceland -- 440 MWe up from 202 MWe in 2005
USA -- 6304 MWe up from 2544 MWe in 2005

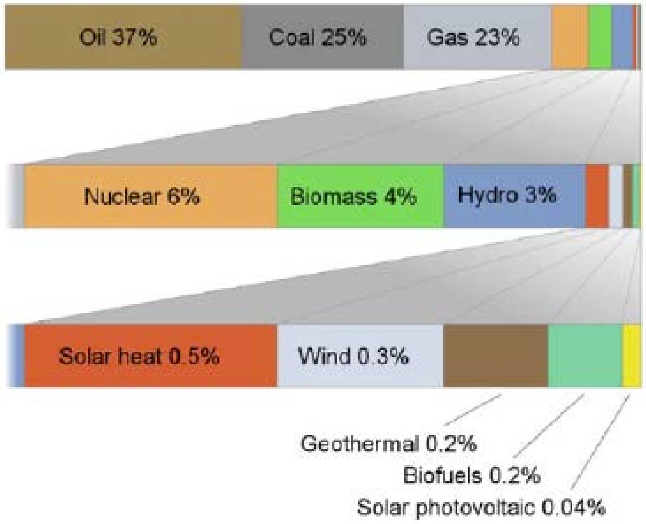


Geothermal energy in Iceland is a significant part of their energy sources.

Larderello started producing on 1904 …. Still going strong!







- Geothermal electricity generates a good fraction of the standard renewables (GWS), more than solar but less than wind.
- It is also used for heating (probably less than solar).
- It enjoys a high capacity factor.
- It has grown steadily but less than wind and solar, which enjoy 20-30%/y over the past few years because of the price drop.

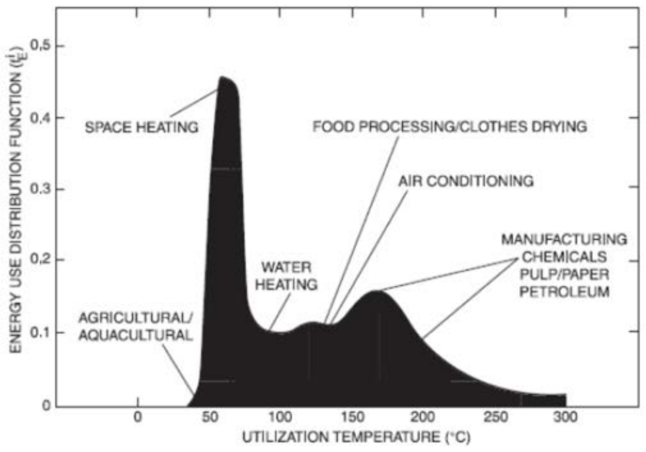
Geothermal energy today for heat and electricity

- From its beginning in the Larderello Field in Italy in 1904, nearly 10,000 MWe of capacity worldwide today
- Additional capacity with geothermal heat pumps (e.g >100,000 MWt worldwide)
- Current costs -- 7–10¢/kWh
- Attractive technology for dispatchable base load power for both developed and developing countries

Condensers and cooling towers, The Geysers, being fitted with direct contact condensers developed at NREL

J Tester, Energy Env. Sci

The non-electric portion of energy use is large and at relatively low temperatures



In the US over 30% of our primary energy is actually used at temperatures < 200°C

Figure 11.5. Fractional energy use distribution as a function of end-use temperature for non-electric applications below 300°C. The function f_E^i at T_i is simply the derivative of the cumulative energy use at that specific temperature T_i. Source: Tester (1982).

Geothermal energy, like low grade solar thermal energy, works well for heating applications.

More than 30% of the US primary energy is used at T < 200C

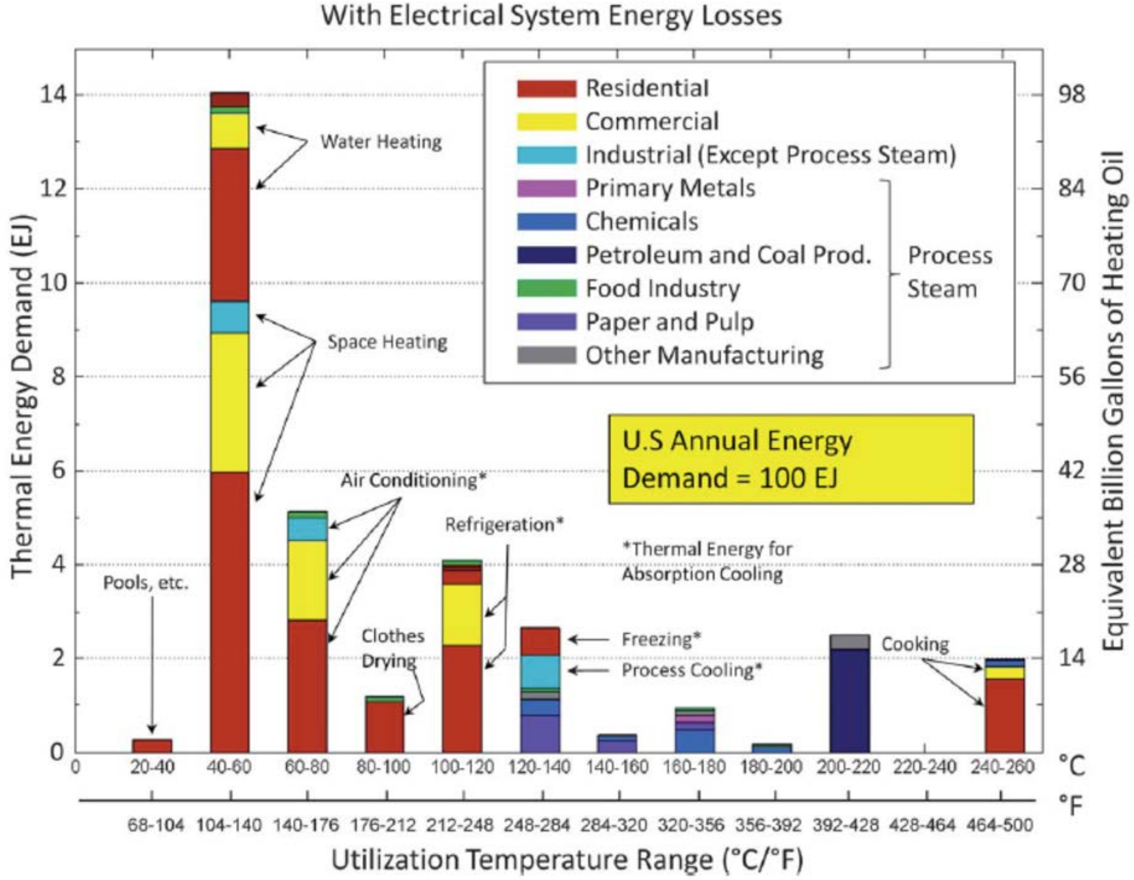
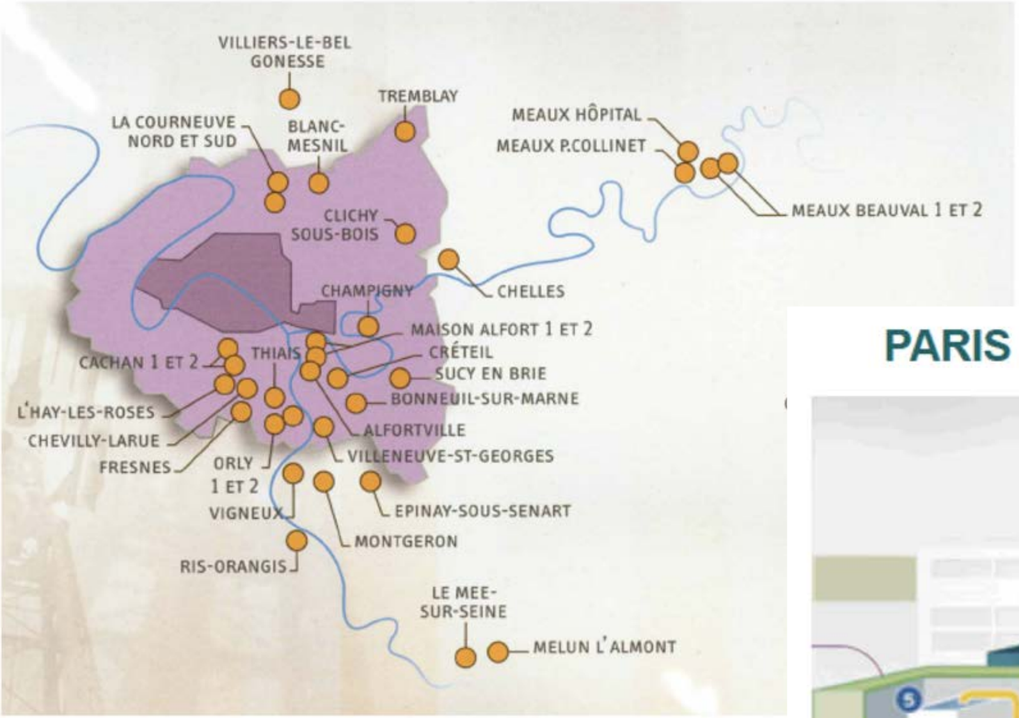
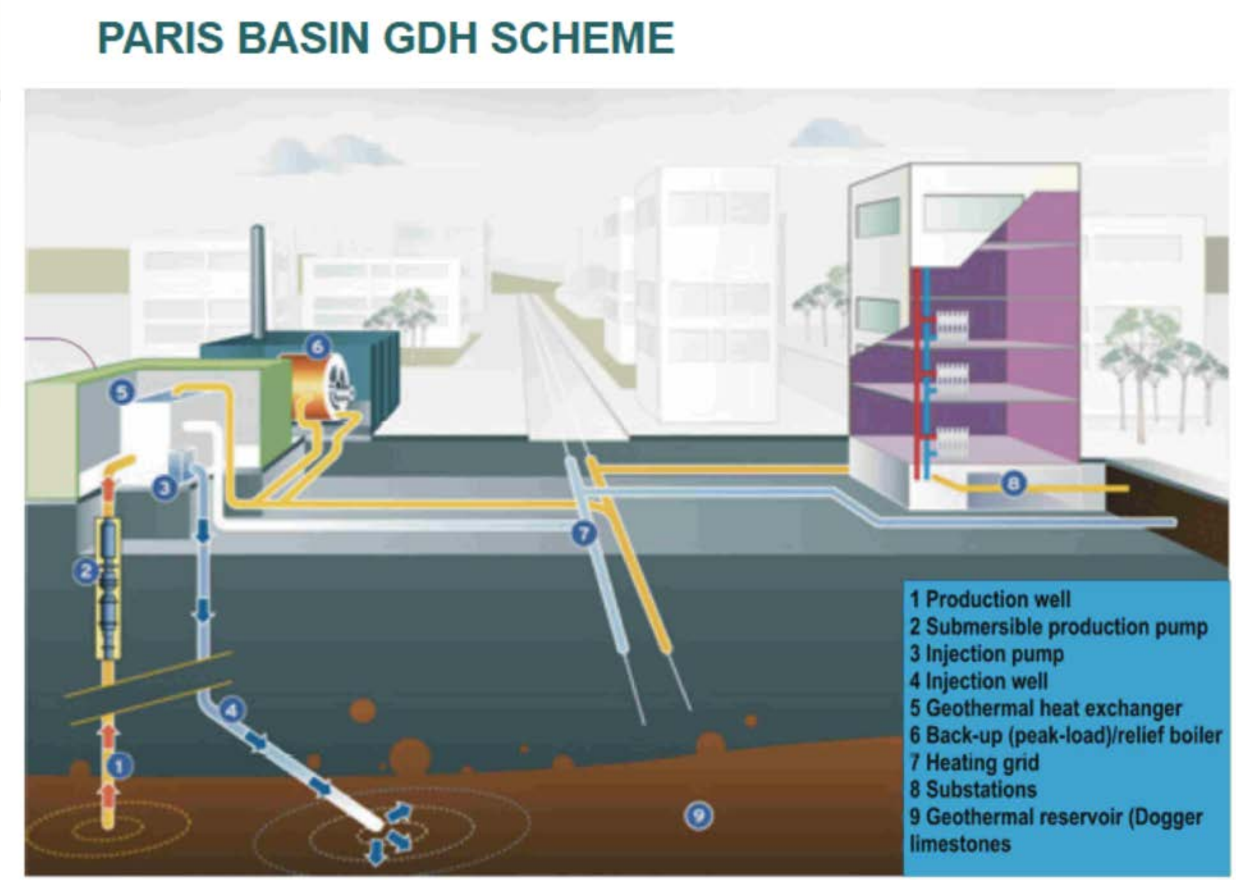


Fig. 1 Estimated thermal energy consumed in America below 260 °C (500 °F).

Location of Paris Basin geothermal district heating doublets 2006 status (source ADEME)



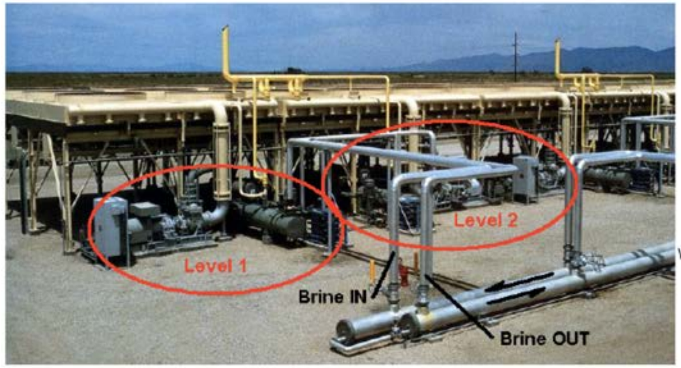
Very effective use of Geo resources
Central/district heating

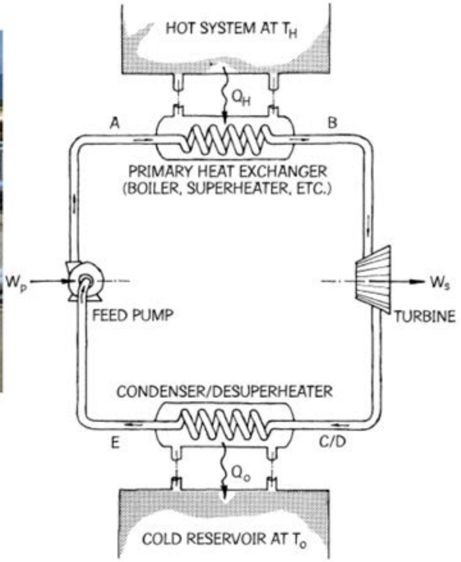


5 MWe organic binary cycle in Nevada using isobutane as a working fluid with no cooling water consumption!

Geothermal power plants tend to be small, 20-80 MWe.
Some are smaller!

Stillwater, Nevada Organic Rankine Cycle Plant





With low T resource, ORC are ideal.

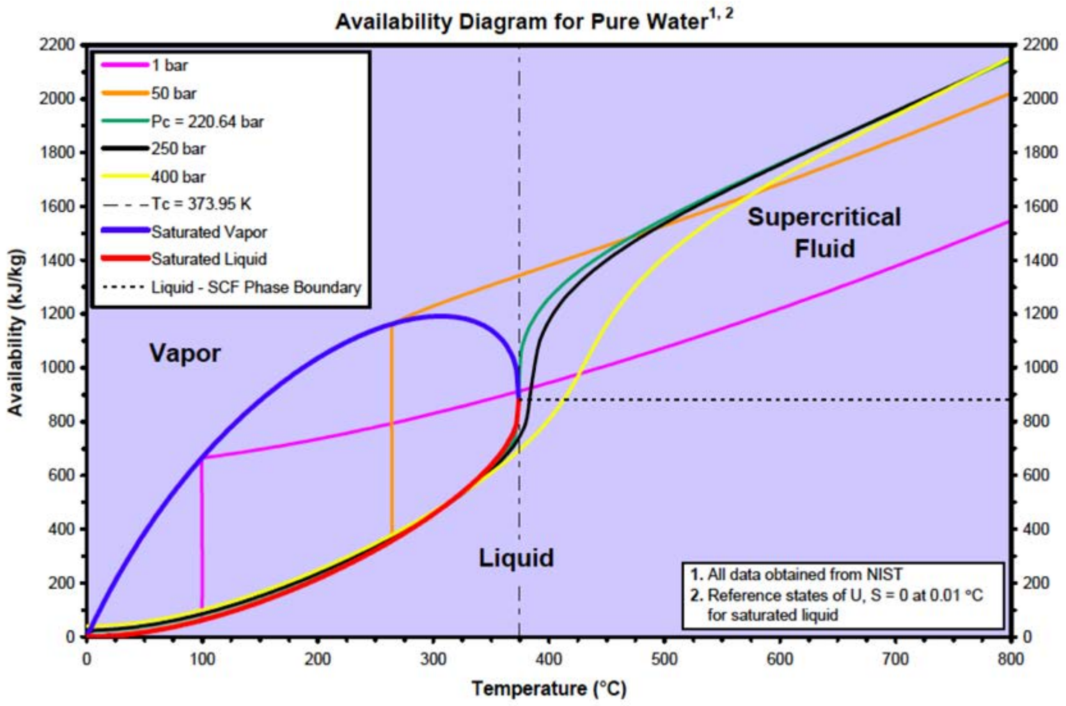
Working fluids requirements for Rankine Cycles:

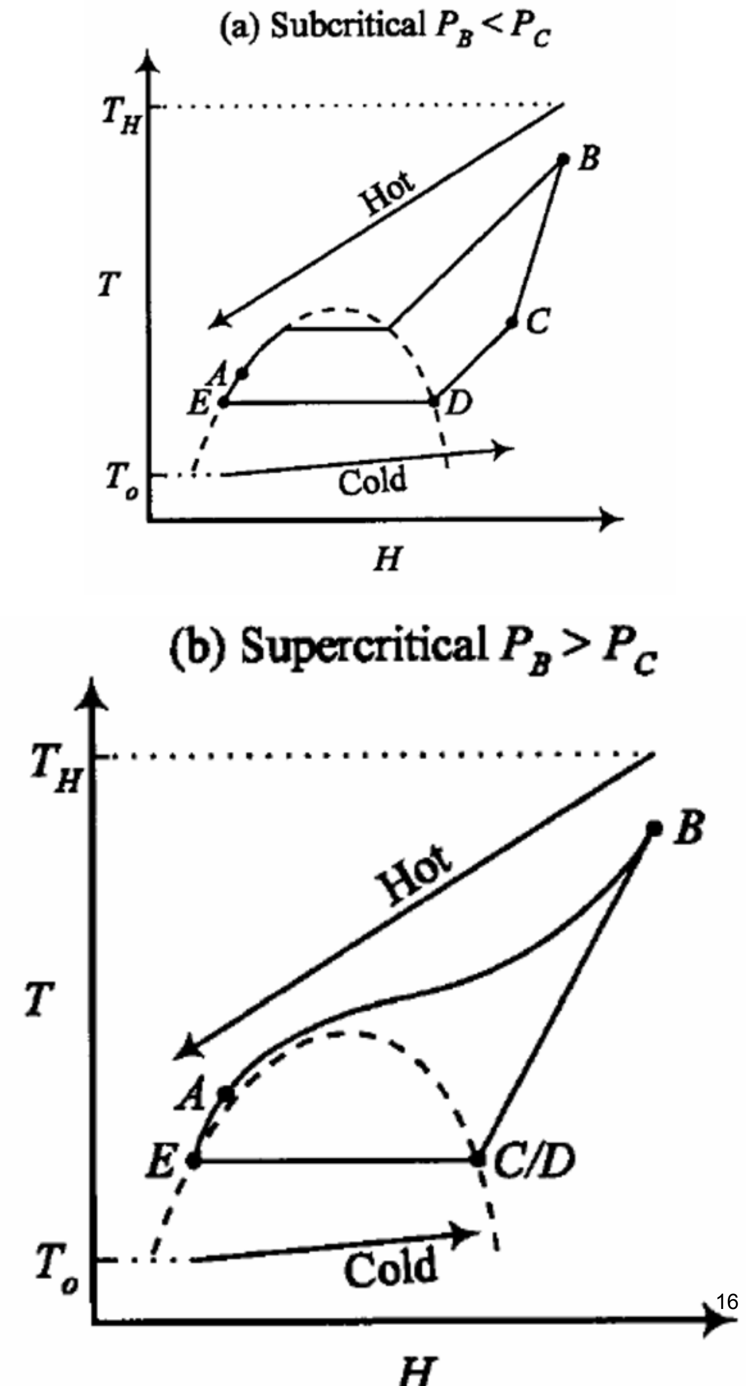
1. High T_c for efficiency but low p_c for simplicity
2. Large enthalpy of evaporation
3. Non toxic, non flammable, non corrosive, cheap ..

Water: p_c=22.088 MPa T_c=374 C, most common
CO_2: p_c=7.39 MPa, T_c=30.4C (low p)

Renewable sources (low to very low T for solar and geothermal):
Ammonia: p_c=11.63 MPa, T_c=132 C.
Propane: p_c= 4.26 MPa, T_c= 97 C
Isobutane, Freon

Max T is low, and Supercritical Cycles must be used to improve efficiency





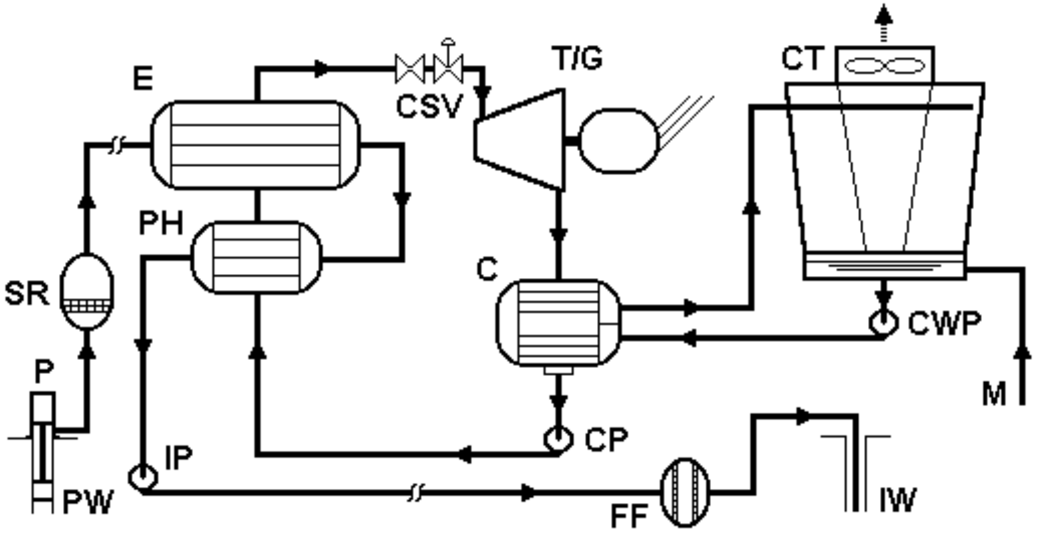
- Availability of working fluid increases sharply when heat is added at constant T, and in the supercritical region.
- Supercritical operation reduces availability loss between source (geo fluid) and working fluid.

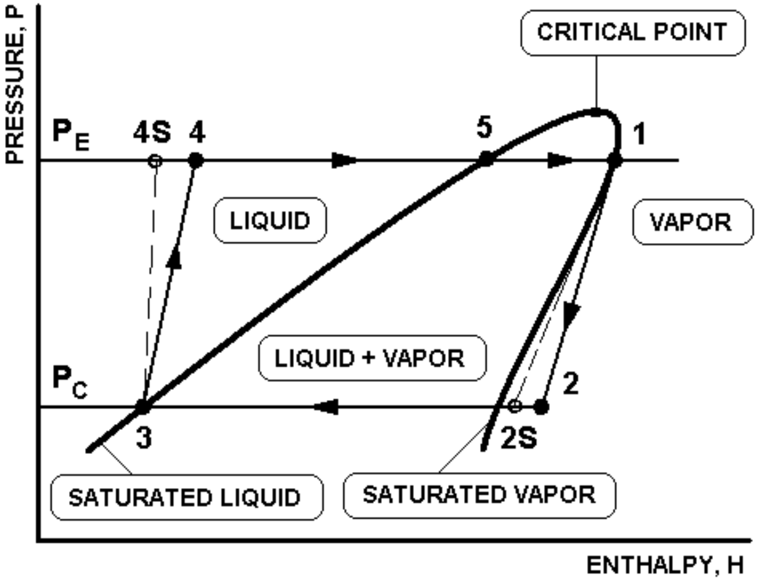
Surface Plant: Binary

An ordinary Rankine cycle with an organic fluid used as a working fluid.

The working fluid is heated in two stages (E and PH), expanded in a turbine, condensed and pumped back.

The Geo fluid is used to supply heat to the working fluid (E and PH) and is returned back to well.





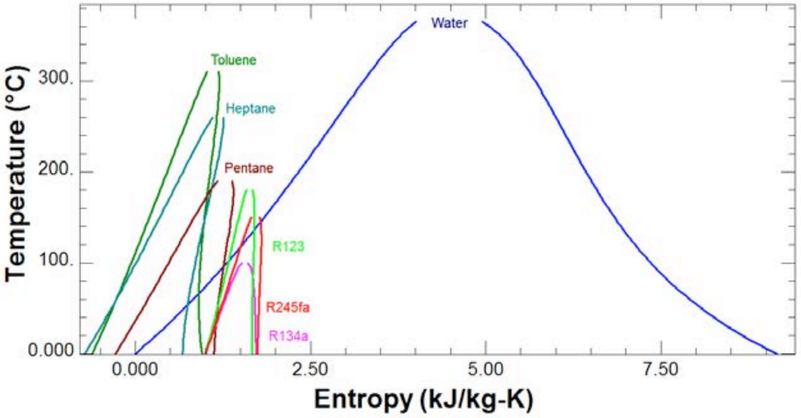
Organic Rankine Cycles

Used in Waste Heat Recovery" as well

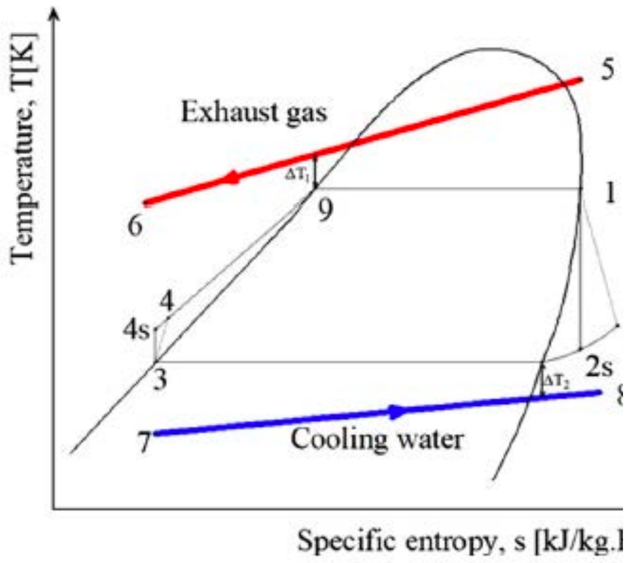
All are Refrigirants, T_b: the boiling point, ODP: Ozone Depletion Potential, GWP Global warming potential

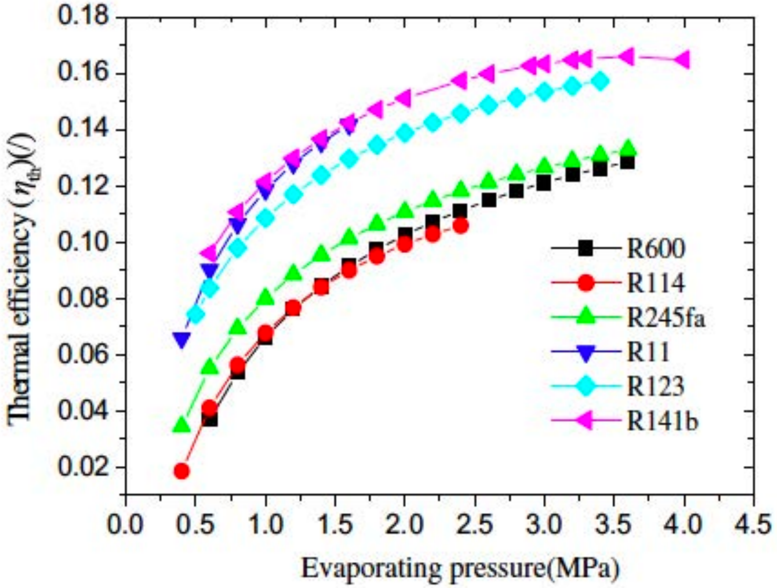
Tchanche etal, Fluid selection for a low temperature solar organic Rankine cycle, Applied Thermal Eng., 29:2468-2476 (2009)

T-s diagram for different organic fluids, normal and "overhang"



Substance		Physical Data				Environmental Data		
								GWP (100 y)
1	R123	152.93	27.8	183.7	3.668	1.3	0.020	77
2	R134a	102.03	26.1	101	4.059	14	0	1430
3	R152a	66.05	-24	113.3	4.520	1.4	0	124
4	R245fa	134.05	15.3	154.05	3.640	7.6	0	950
5	R290	44.10	42.10	96.68	4.247	0.041	0	~ 20
6	**R600**	**58.12**	**-0.5**	**152**	**3.796**	**0.018**	**0**	**~ 20**





(left) The *T-s* diagram of an ORC using a fluid with an overhang saturation curve, and (right) using a number of different working fluids. The analysis applied realistic models for the different cycle components and working fluid equation of state. The cycle operates on engine exhaust 250 °C. Results show the impact of the cycle high pressure Tian et al., *Energy*, 47, 125–136, 2012.

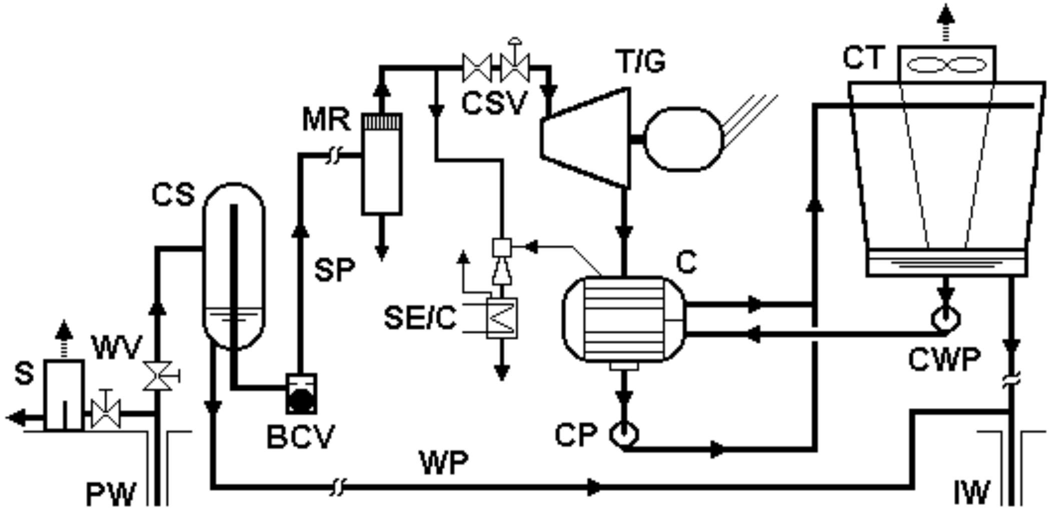
Surface Plant: Flash

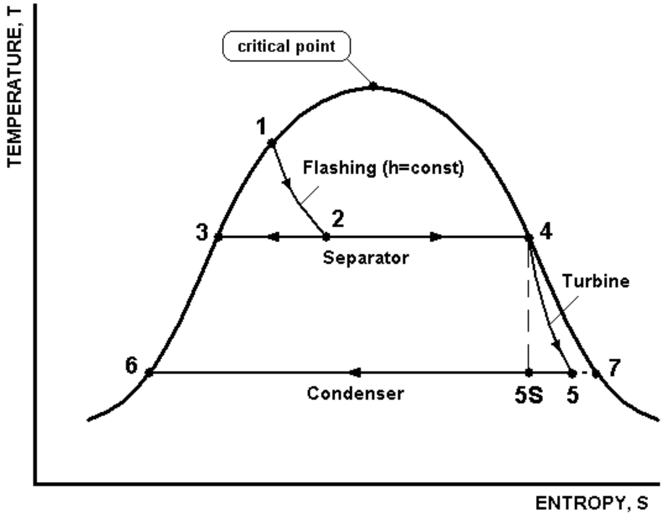
A simpler cycle in which the Geo fluid is used as a working fluid.

First it is flashed to a lower pressure, with steam then expanded in the turbine, condensed, pumped back and returned to the well.

The water remaining after flashing is returned to the well directly.

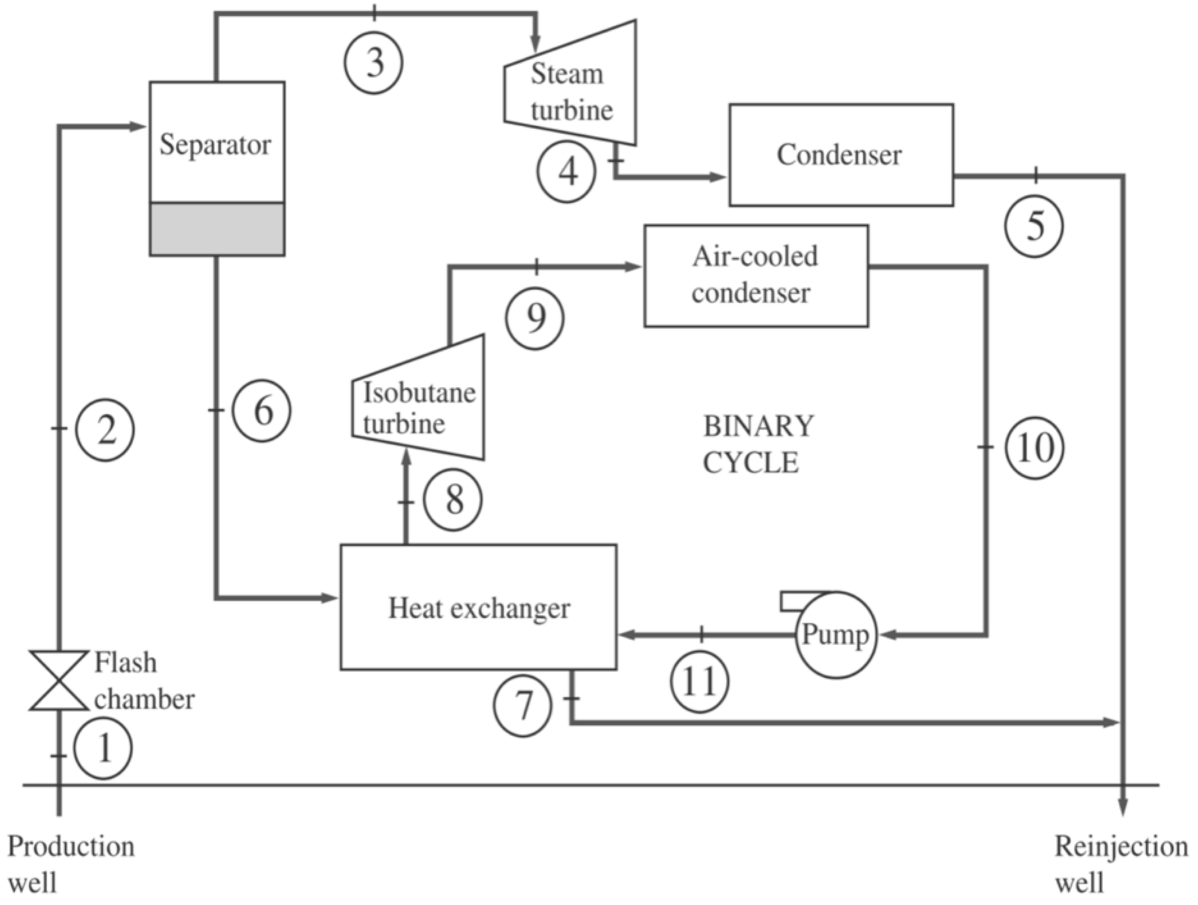
The geo steam is conditioned before expansion.



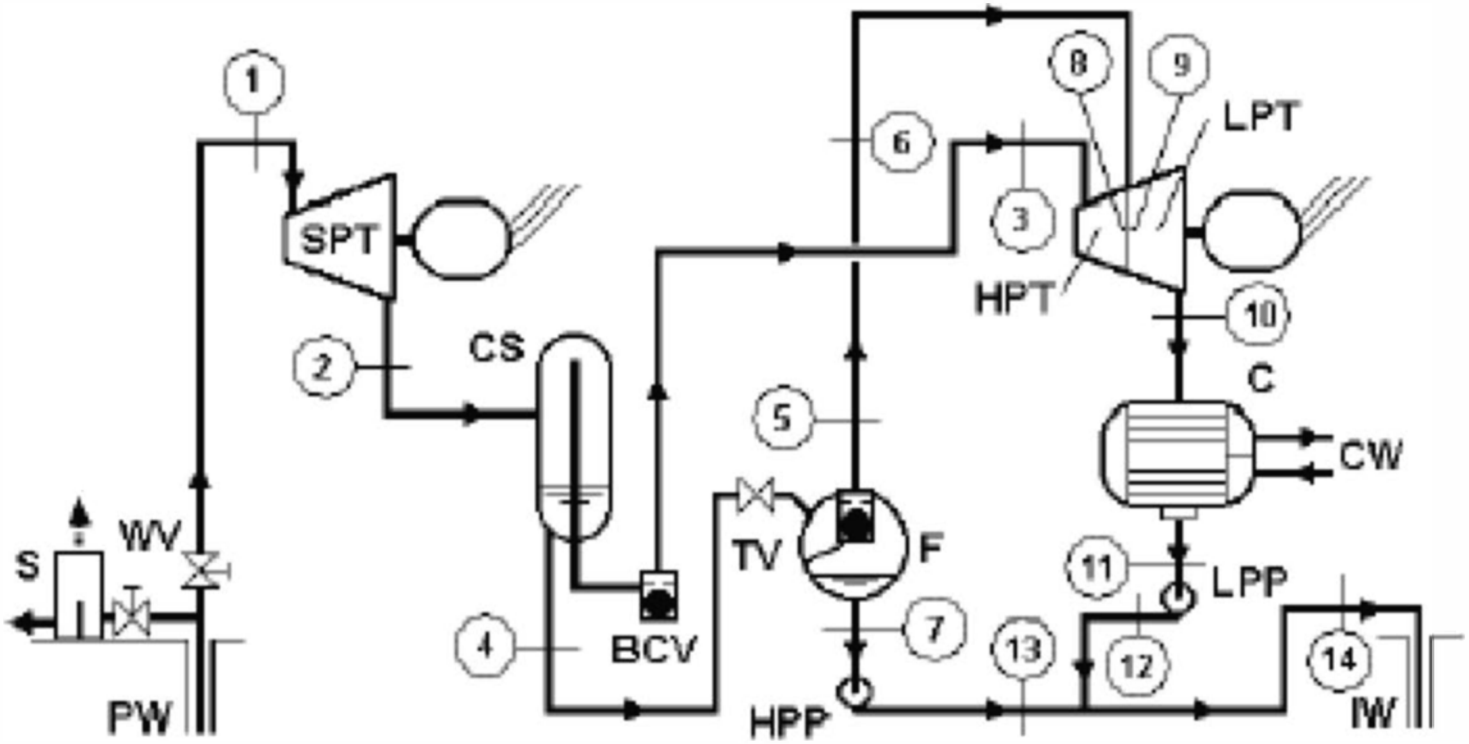


Example 9.1

- Hybrid plant: single flash to separate the geo-fluid into steam and liquid.
- A steam turbine extracts work from the steam.
- A binary cycle (iso-butane) heated by the liquid produces more work.

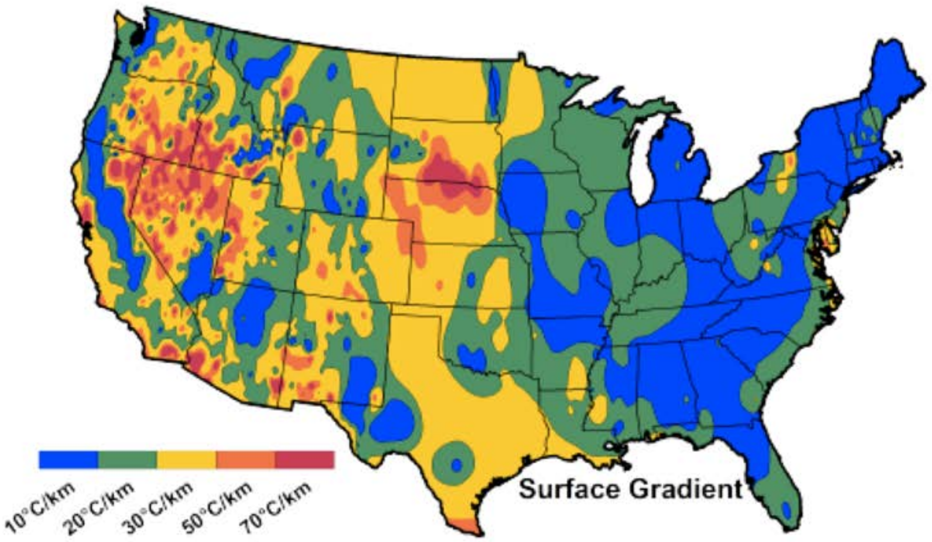


See solution.
Efficiency of steam by itself is 7.6%
Efficiency of hybrid plant is 10.6%

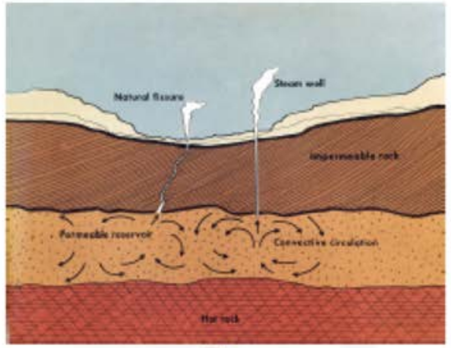


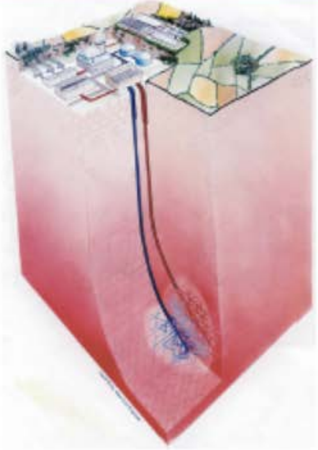
Trilateral supercritical vapor cycle

Is there a feasible path from today's hydrothermal systems with 3000 MWe capacity to tomorrow's Enhanced Geothermal Systems (EGS) with 100,000 MWe or more capacity by 2050 ?



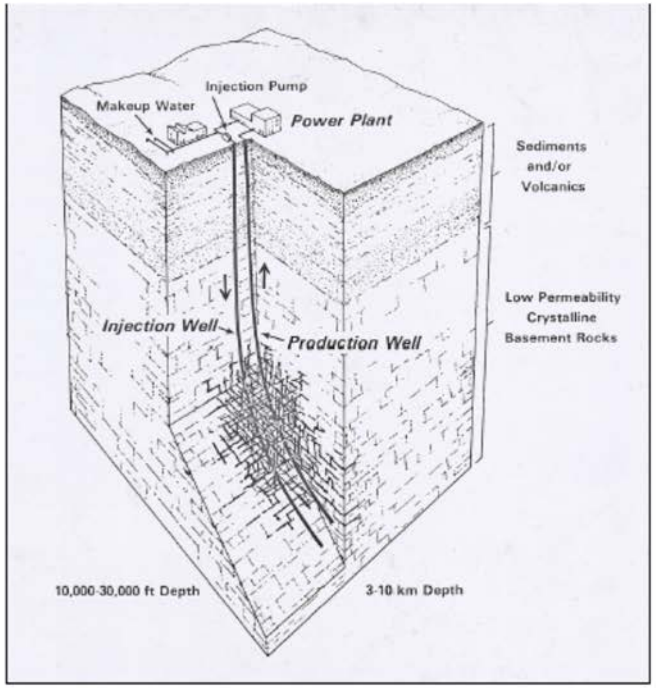
Average surface geothermal gradient
from Blackwell and Richards, SMU (2006)

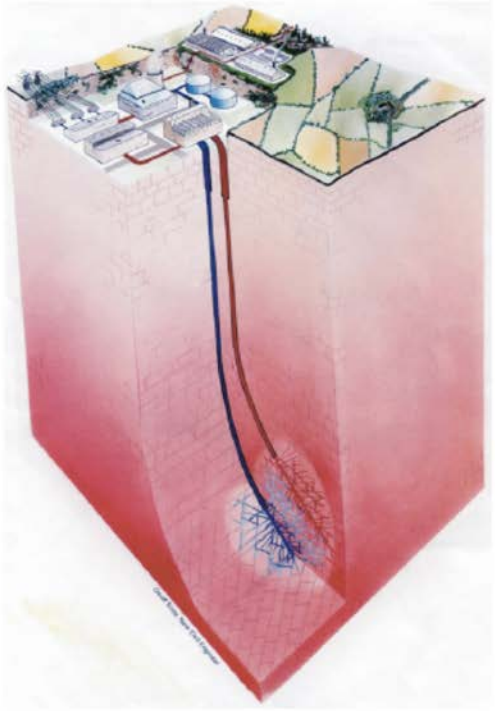




Significant fraction of the land area has 20 C/km gradient or higher. At 6 km deep, it is possible to recover heat at 120 C or higher that can be used in low grade geothermal plant. However, there is little fluid down there!

Enhanced/Engineered Geothermal Systems (EGS)



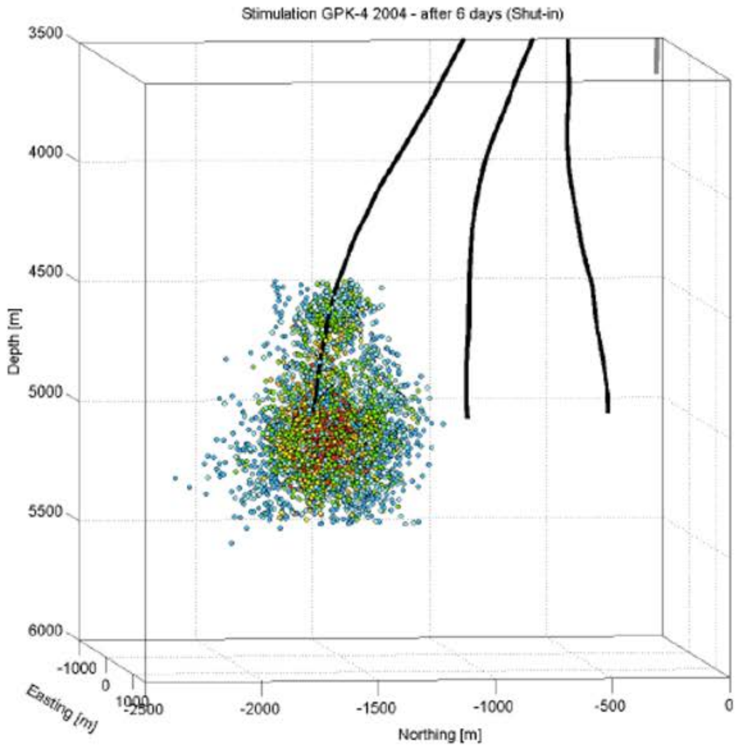


“fracking is necessary: crack the rock by drilling deeps well, first vertically then horizontally, inject water (and sand and possibly some chemicals) to further fracture the rock and keep the small cracks open Now inject cold water and recover it as warm water from another well”

Developing stimulation methods to create a well-connected reservoir

The critical challenge technically is how to engineer the system to emulate the productivity of a good hydrothermal reservoir

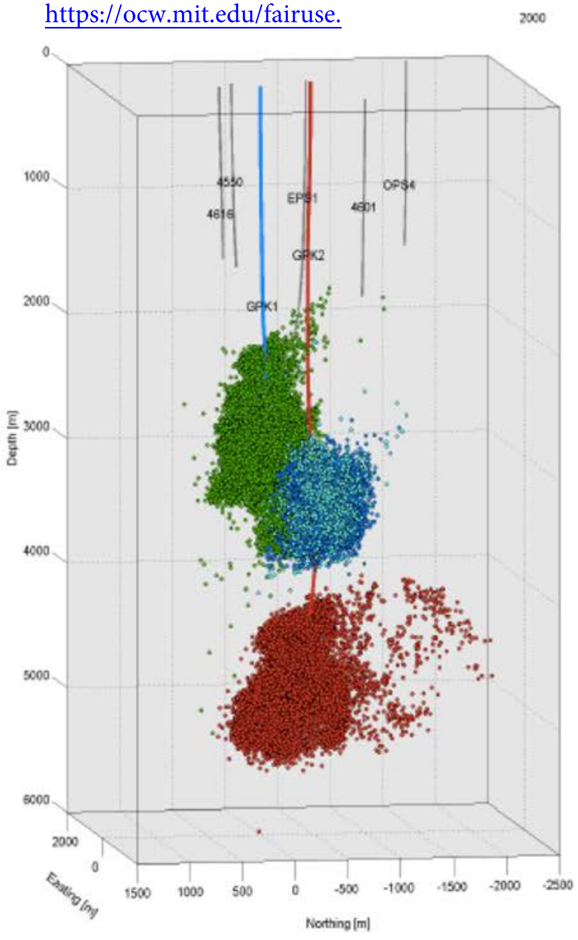
Connectivity is achieved between injection and production wells by hydraulic pressurization and fracturing



"snap shot" of microseismic events during hydraulic fracturing at Soultz from Roy Baria

Drilling deep holes may cause micro seismic events (and sometimes more than micro that can lead to shutting down the operation).

R&D focused on developing technology to create reservoirs That emulate high-grade, hydrothermal systems



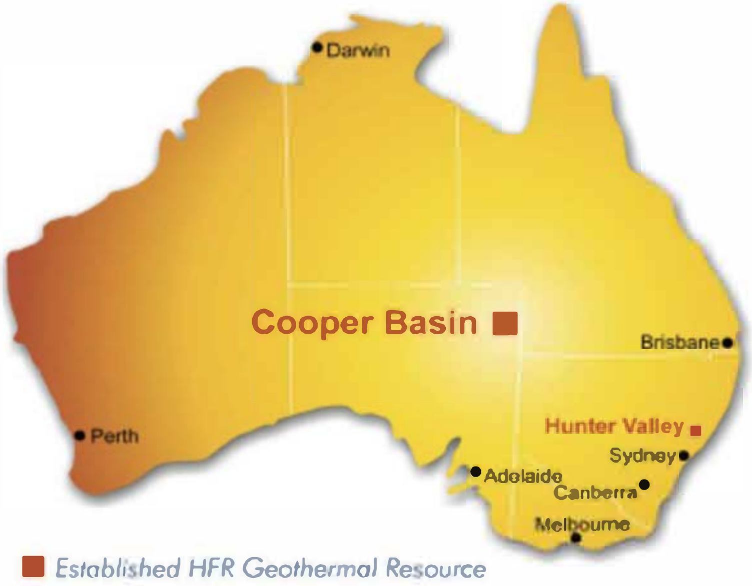
Soultz, France from Baria, et al.

30+ years of field testing at

- Fenton Hill, Los Alamos US project
- Rosemanowes, Cornwall, UK Project
- Hijori, et al , Japanese Project
- Soultz, France EU Project
- Cooper Basin, Australia Project, et al.

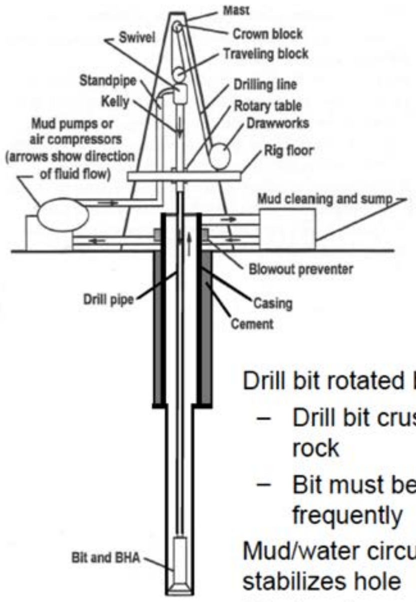
has resulted in much progress and many lessons learned

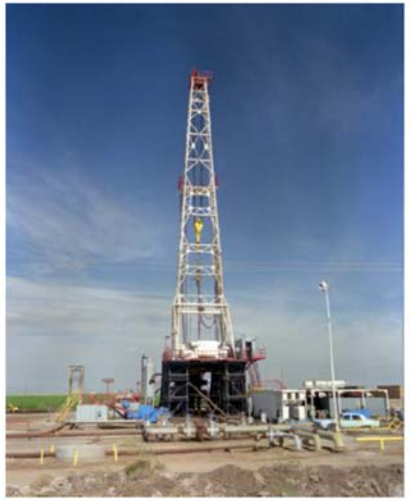
- directional drilling to depths of 5+ km & 300+°C
- diagnostics and models for characterizing size and thermal hydraulic behavior of EGS reservoirs
- hydraulically stimulate large >1km³ regions of rock
- established injection/production well connectivity within a factor of 2 to 3 of commercial levels
- controlled/manageable water losses
- manageable induced seismic and subsidence effects
- net heat extraction achieved



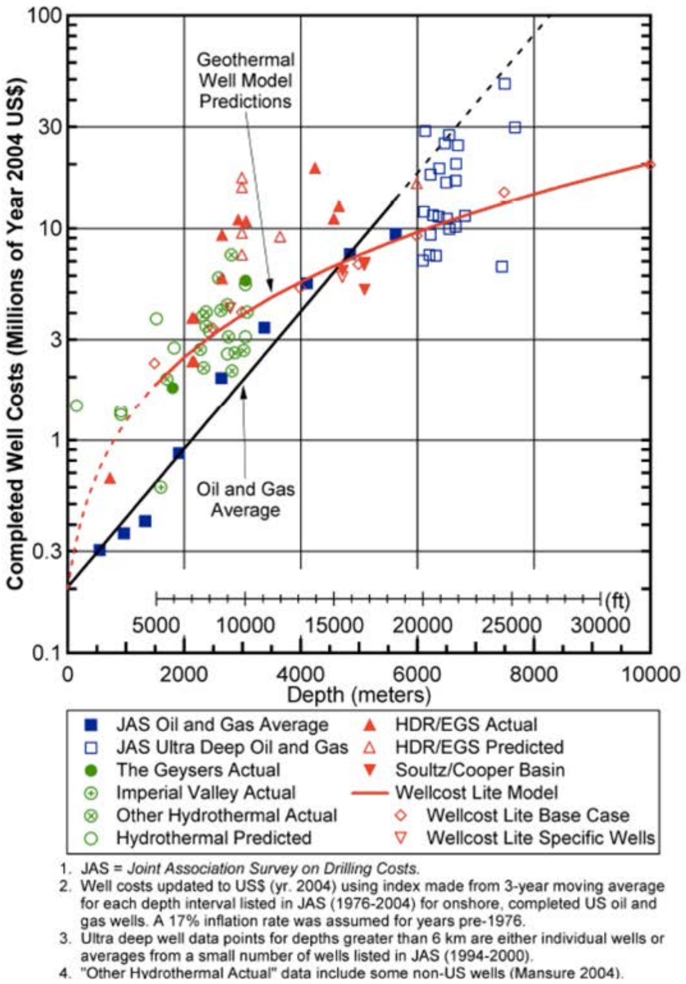
17 March 2008 --
Wellhead flow rate 18 kg/s
at 275 bar, 208°C and rising

Today's Conventional Rotary Drilling



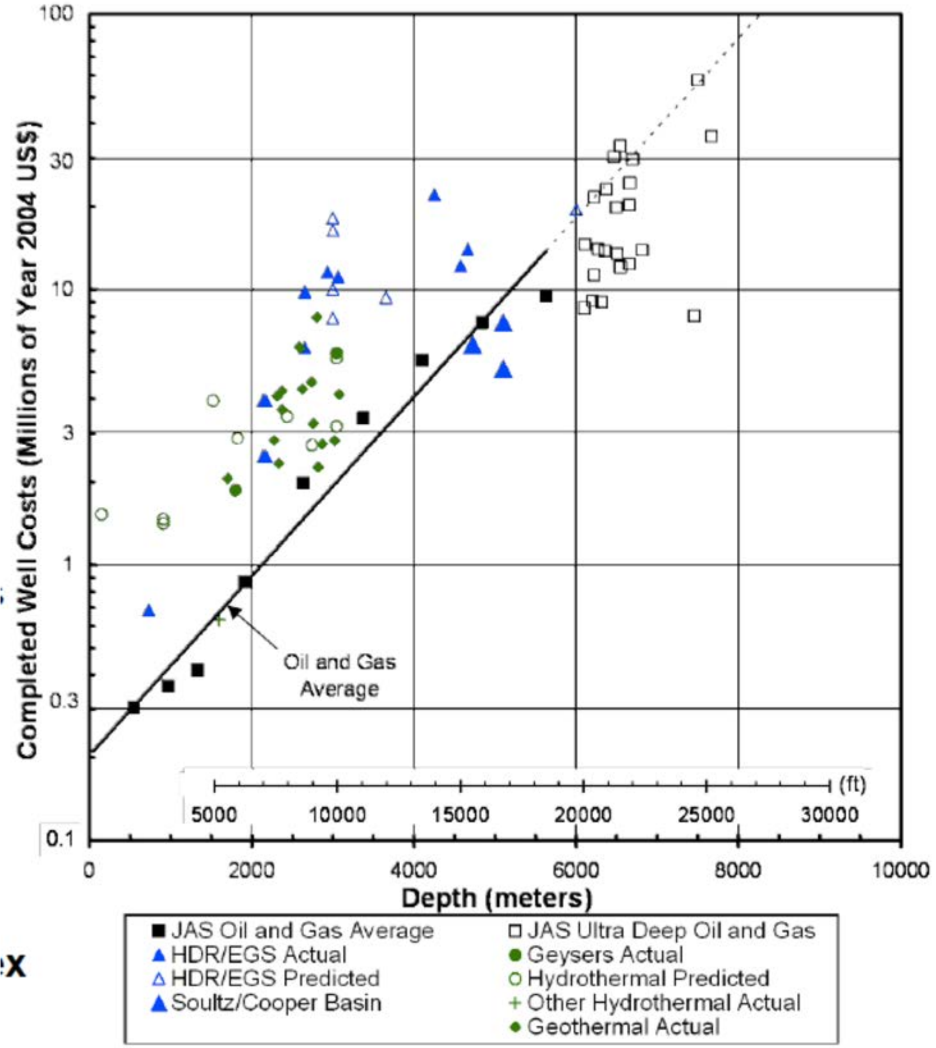


- Drill bit rotated by drill string
  - Drill bit crushes and grinds rock
  - Bit must be replaced frequently
- Mud/water circulation cleans bit, stabilizes hole
- Steel casing and cement used to secure hole

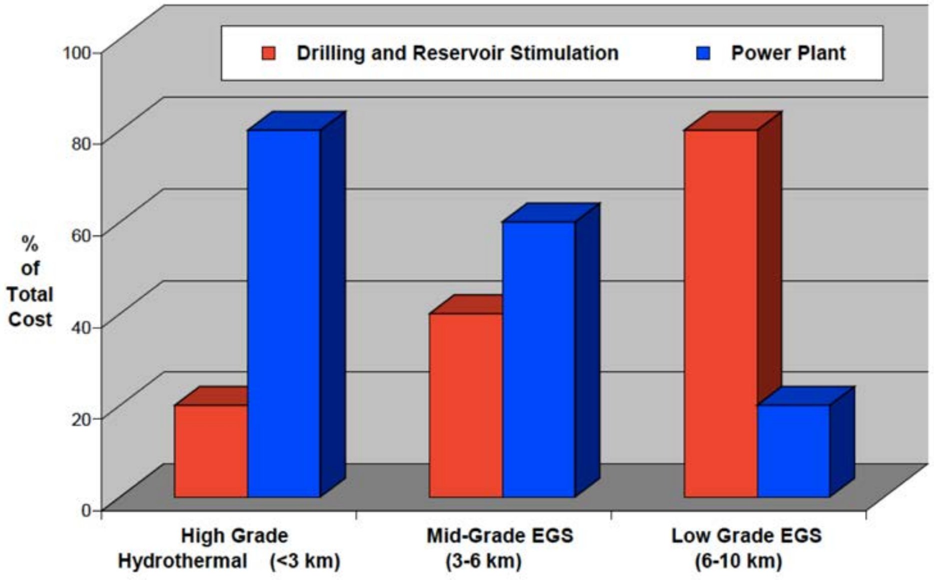


Drilling costs for geothermal wells compared to oil and gas wells

Cost depends on nature of rock, location, formations, etc.



As EGS resource quality decreases, drilling and stimulation costs dominate



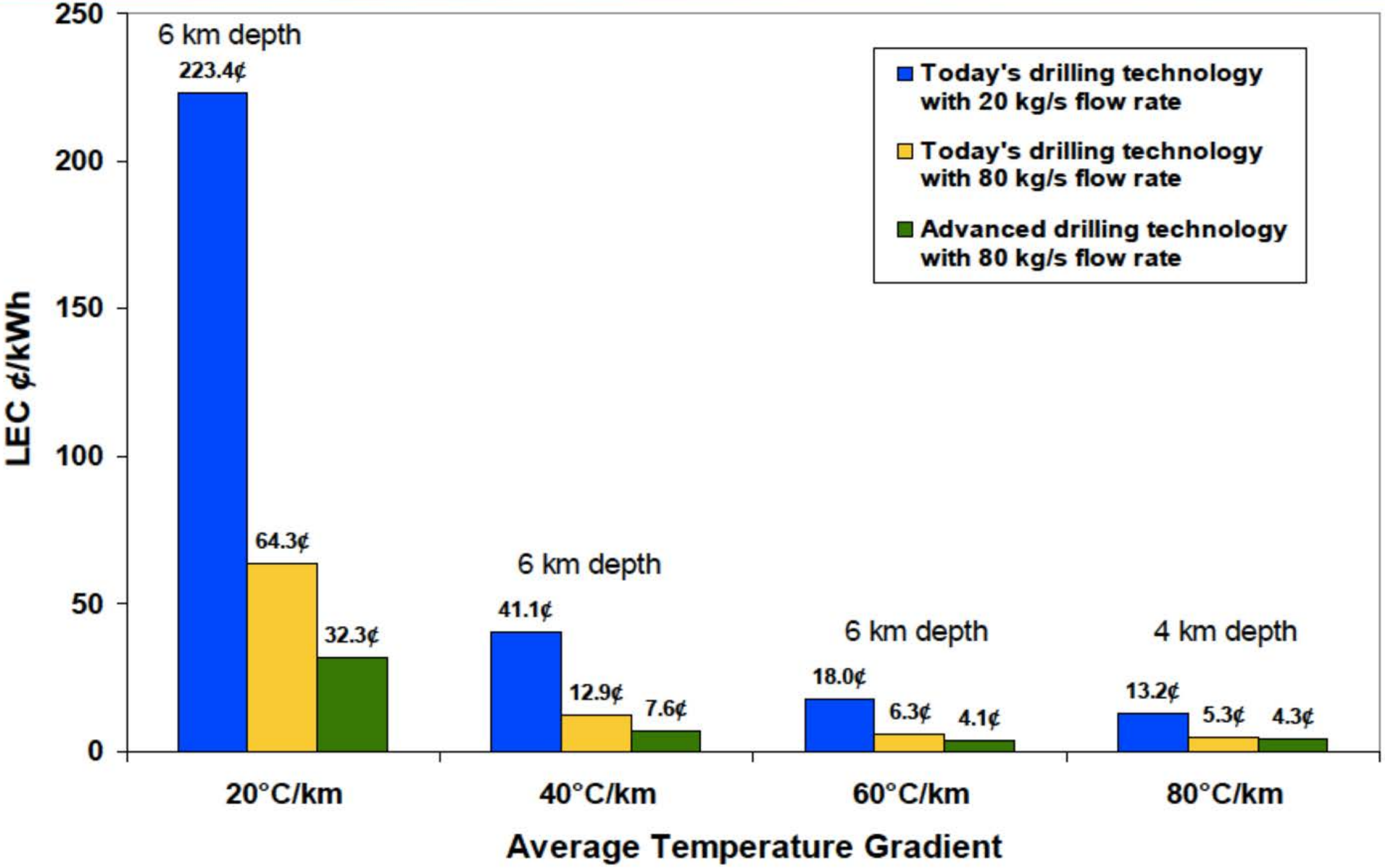
The "Laws" Geothermal Economics

1st Law -- Completed well cost increases exponentially with depth

2nd Law -- Power plant cost decreases linearly with temperature

3rd Law --As resource quality decreases drilling costs dominate

Levelized energy costs vary with resource grade and reservoir productivity and drilling costs



- **Supercritical water**
  - Pressures of > 220 bar
  - Temperatures of over 2500 K
- **Heat and momentum Transport**
  - Turbulent flow
  - Jet impinging against rock
- **Detailed chemical kinetics**
  - H_2-O_2 combustion at high pressures → kinetic mechanisms unknown