Applied Geothermics – Geothermal Energy Use

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APPLIED GEOPHYSICS AND GEOTHERMAL ENERGY

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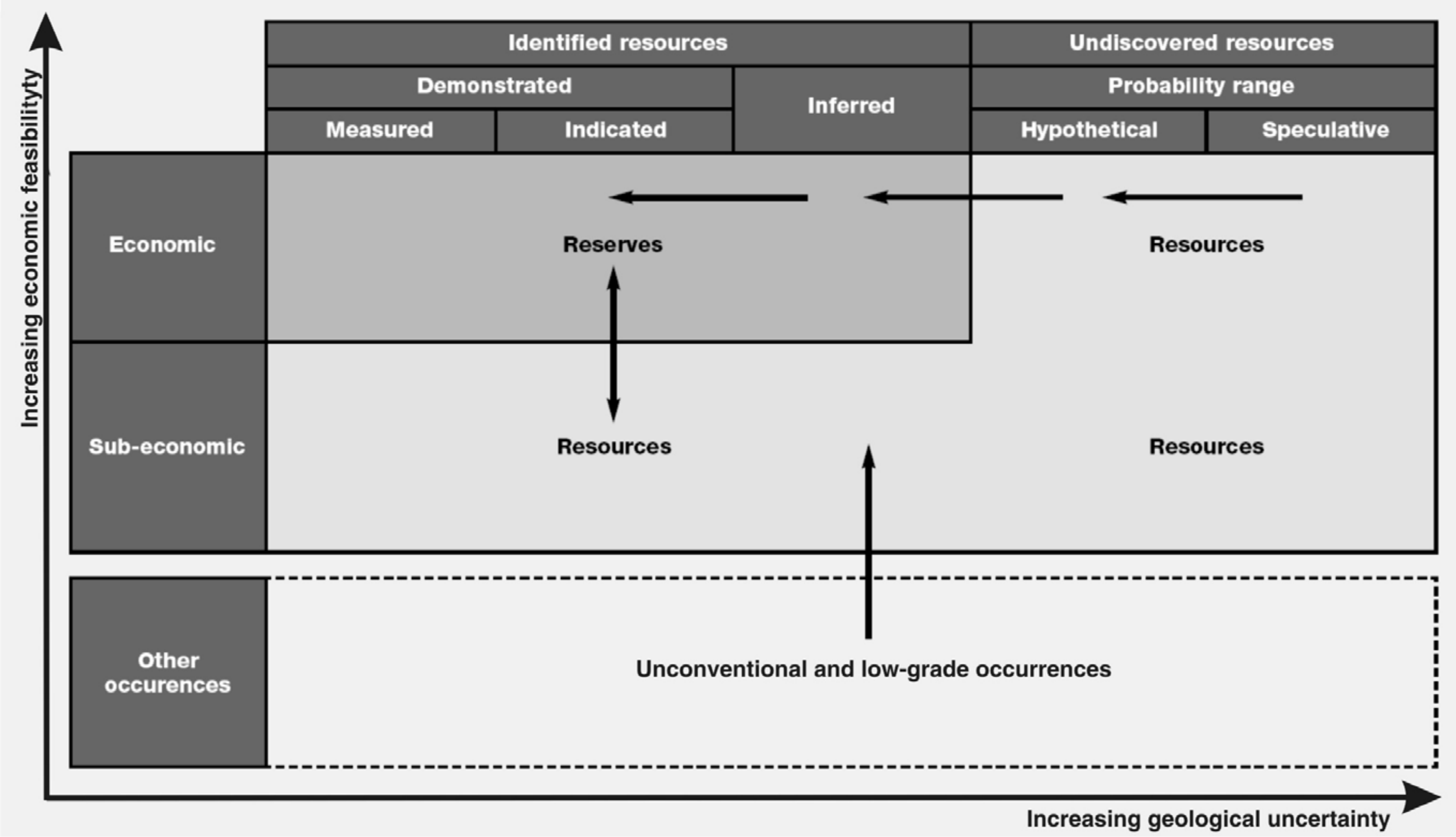
Topics discussed

- Types of geothermal resources

- Types of geothermal energy use
  - Direct use
    - Space heating and cooling
    - Commercial and industrial applications
  - Power generation

- Technological and economical aspects of geothermal energy
  - Direct use
    - Earth coupled heat extraction systems
    - Hydrothermal heating systems
  - Power generation
    - Natural steam power plants
    - Binary power plants
    - power plants for Hot Dry Rock or enhanced geothermal systems
    - Technical, economic and ecological aspects

Types of geothermal resources



McKelvey-diagram for classification of resources

Types of geothermal resources

Definition of geothermal resource categories and their estimated global potential.

Resource category	Energy (EJ; TW h)
Accessible resource base: heat in place = amount of heat which can be produced theoretically from the topmost 5 km	**140,000,000** **38,920,000,000**
Useful accessible resource base	600,000 166,800,000
Resources: fraction of the accessible resource base which is expected to become economical within 40-50 years	5,000 1,390,000
Reserves: fraction of the accessible resource base which is expected to become economical within 10-20 years	500 139,000

Accessible geothermal resource base by region.

Region	Energy (EJ)	Percentage of world total
North America	26,000,000	18.6
Latin America and Caribbean	26,000,000	18.6
Western Europe	7,000,000	5.0
Eastern Europe and former Soviet Union	23,000,000	16.4
Middle East and North Africa	6,000,000	4.2
Sub-Saharan Africa	17,000,000	12.1
Pacific Asia (excl. China)	11,000,000	7.9
China	11,000,000	7.9
Central and South Asia	13,000,000	9.3
Total	**140,000,000**	**100.0**

Types of geothermal resources

hydrothermal: hot water or steam at moderate depth (1 km – 4 km) with temperatures of up to 350 °C in a permeable region of porous rock with active free or forced convection systems;

geopressured: hot, high-pressure reservoir brines containing dissolved natural gas (methane). Energy content about 58 % thermal, hydrocarbon chemical 32 %, and hydraulic 10 % at best;

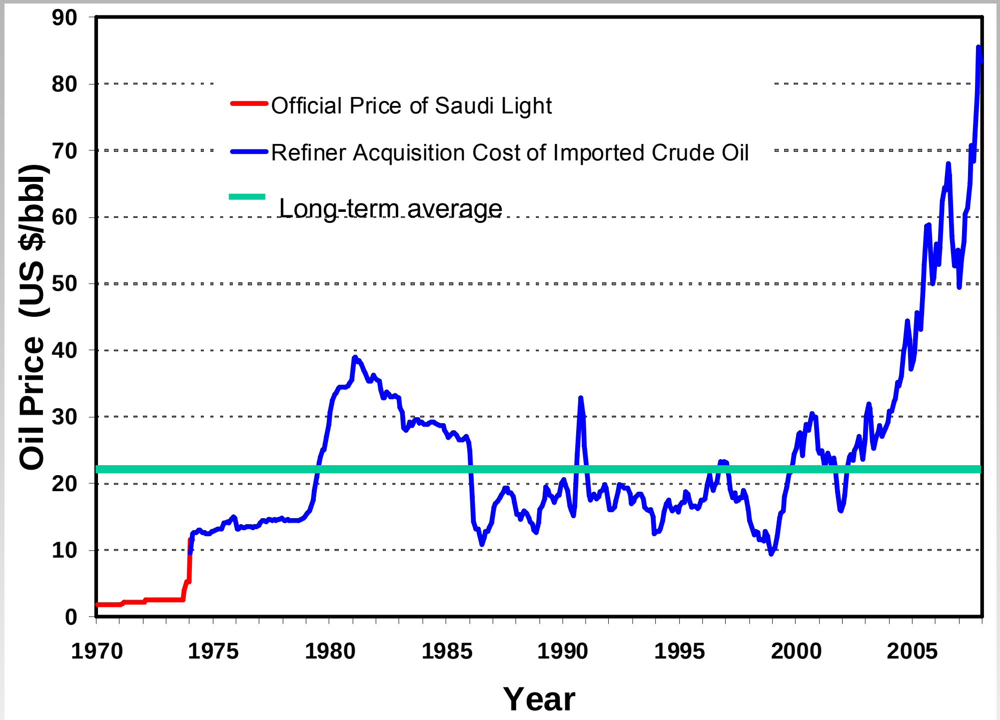
hot dry rock (HDR) or enhanced geothermal systems (EGS): fluids not produced spontaneously. Systems require stimulation before energy can be extracted;

magma: molten rock at temperatures of 700 °C – 1200 °C at accessible depth (< 7 km).

Classification of geothermal reservoirs.

Type	Resource	Temperature range (°C)	Energy content
Water dominated	Warm water	< 100	Low enthalpy
	Wet steam	100 - 150	Medium enthalpy
Vapor dominated	Dry steam	> 150	High enthalpy

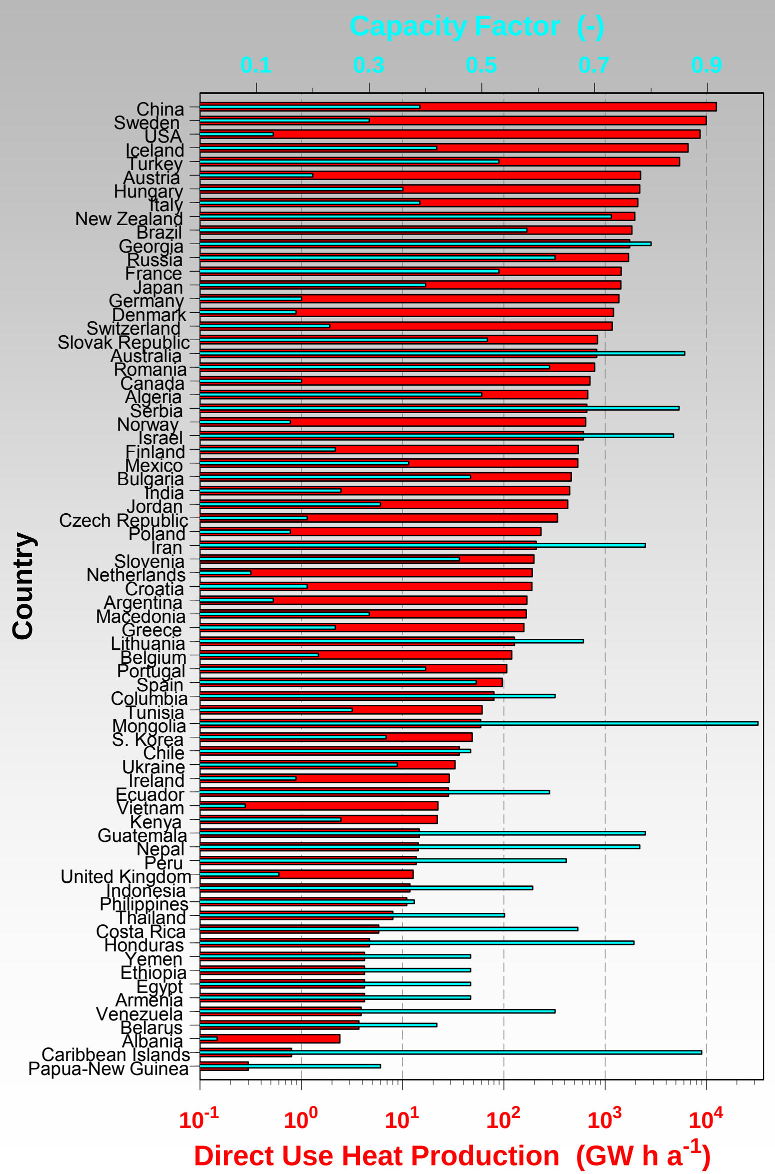
Competitiveness



Competitiveness of renewables defined with respect to energy prices based on fossil fuels, i. e. oil, gas, and coal.

Common reference: **oil price** – extremely volatile, adjusting not only to demand and supply in a free market but also determined by political boundary conditions. **Fluctuations of more than 120 % around its 35-year average of ~21 US $**. Accordingly, competitiveness of geother-mal energy varied in the past, becoming more or less attractive in times of high or low oil prices, respectively.

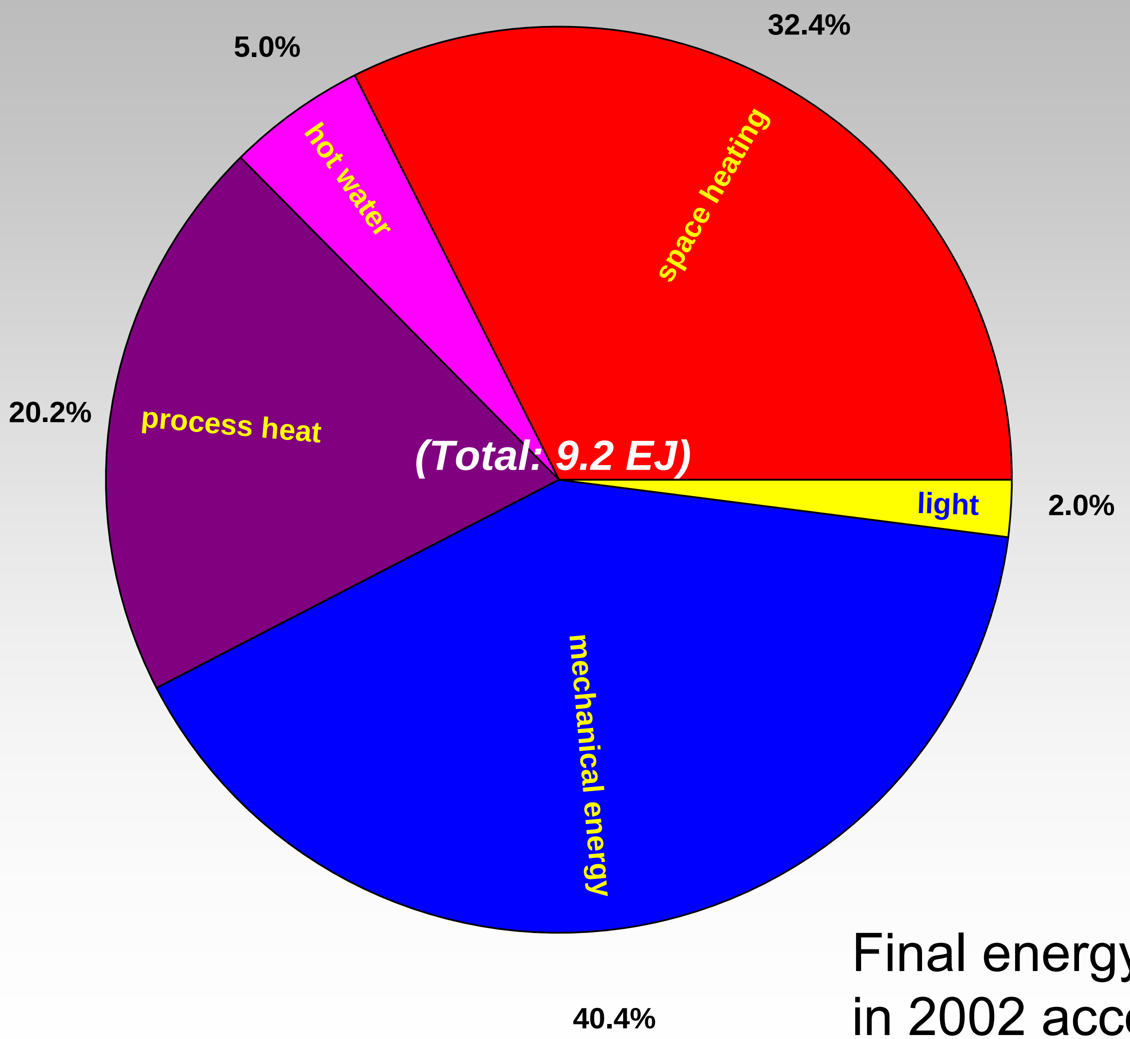
Geothermal direct use 2005



Geothermal direct use by country in 2005:

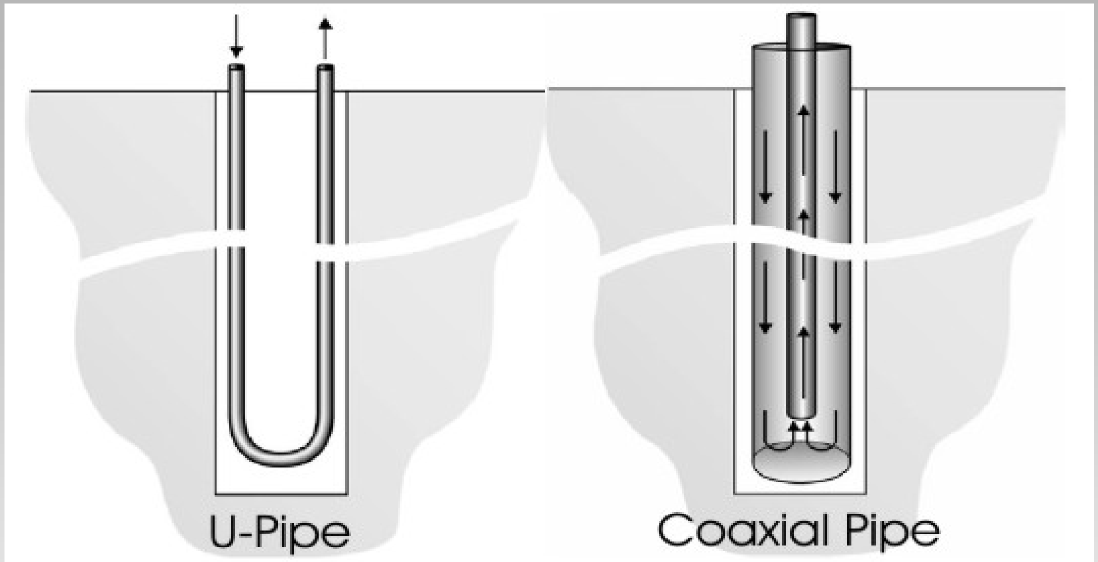
- National contributions to the **global annual production** of about **261 PJ (72.6 TW h)** of direct use geothermal heat (*big red bars*)
- Capacity factors (energy produced vs. year-round energy production at full capacity; *slim blue bars*)

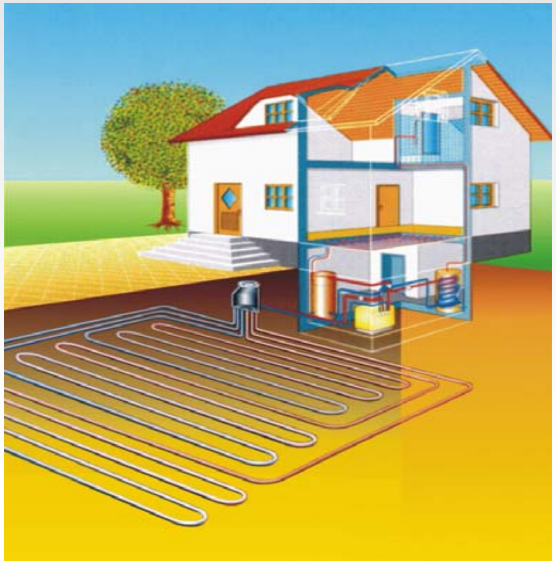
Space heating



Final energy consumption in Germany in 2002 according to use

Space heating: Earth coupled heat extraction





Left: Shallow borehole heat exchanger (top) and horizontal Earth coupled heat exchanger (left)

Right: Two basic pipe arrangements used in borehole heat exchangers

Space heating: Earth coupled heat extraction

Horizontal Earth coupled heat exchangers: Pipe systems buried in the ground below the freezing depth. Useful if sufficient surface area available for installation. More rarely installed for space heating and cooling of buildings than vertical borehole heat exchangers.

Shallow borehole heat exchangers: One or several U-pipes installed and backfilled in a borehole; most frequent configuration consisting of two U-pipes arranged at an angle of 90°. Coaxial pipe arrangements also used, mostly for deeper boreholes.

Shallow borehole heat exchangers vary in depth between 50 m – 250 m. Heat extracted from isolated primary circulation within U-pipes or horizontal pipe systems into secondary circuit. Require heat pump for suitable input temperatures of 40 °C – 70 °C for surface heating elements (floor, wall, ceiling) or conventional radiators, respectively. Typical **specific power** per unit length: **40 W m^{-1} – 55 W m^{-1}** ± 16 W m^{-1}.

Space heating

Top producers of geothermal heat by ground-source heat pumps in 2005

Country, population (10^6)	Number of ground-source heat pumps	Annual heat production (TJ)	Installed power (MW_{th})	Per capita annual heat production (MJ)
Sweden, 9	200,000	**28,800**	2,000	**3200**
USA, 294	**500,000**	13,392	**3,720**	46
Germany, 82	51,000	4,212	780	51
Canada, 32	36,000	1,080	435	34
Switzerland, 7	27,500	2,268	420	**324**
Austria, 8	23,000	1,332	275	167

Space heating: Earth coupled heat extraction

<u>*Ground-source heat pump systems:*</u>

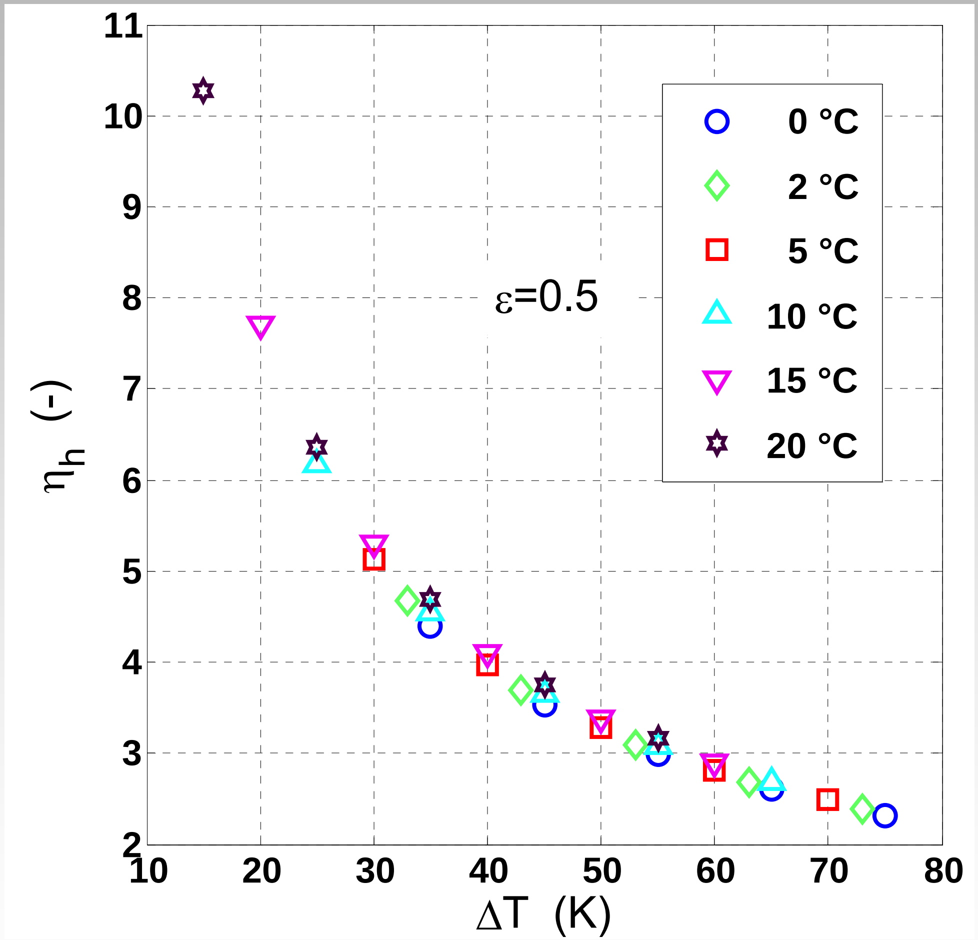
- coefficient of performance (COP) – output energy (heat) over input energy (e.g. electricity for the compressor). Different in the heating and cooling modes: $COP_h > COP_c$
- efficiency η – ratio of heating/cooling power and input power (electric, natural gas):

$$\eta_{hot,max} = T_{warm}/\Delta T = 1/\eta_{Carnot}; \quad \eta_{cold,max} = T_{cold}/\Delta T; \quad (\Delta T = T_{warm} - T_{cold}, \ T \text{ in K})$$

- heat pumps - like thermal power stations – don't operate at maximum theoretical thermodynamic efficiency due to various factors (e.g. heat losses, energy required to drive the pumps for the primary circulation, etc.) Effective efficiency η_h or η_c of a heat pump in heating or cooling modes equals the theoretical maximum efficiency $\eta_{h,\ max}$ or $\eta_{c,\ max}$ diminished by the so-called exergy factor ε=X/E, where exergy X = E-A is the fraction of energy E which can be freely converted into other forms of energy (A: unconvertible „anergy“):

$$\eta_h = \varepsilon\, \eta_{h,max} \quad (\eta_c = \varepsilon\, \eta_{c,max}); \quad \text{with} \quad 0.4 \le \varepsilon = X/E \le 0.5$$

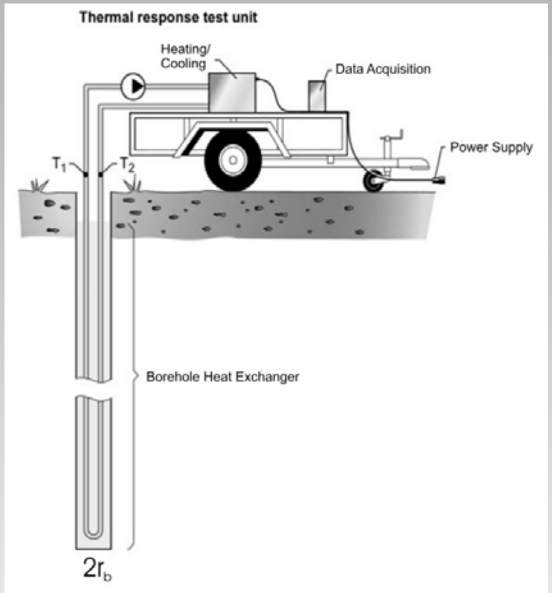
Space heating: Earth coupled heat extraction



Groundwater heat pumps use water in both circuits: $T_{cold} \approx 10$ °C in moderate latitudes; in lower or higher latitudes T_{cold} varies accordingly

borehole heat exchanger heat pumps are brine-water heat pumps, using some sort of brine in the primary, ground-coupled circuit, and water in the secondary one. Often $T_{cold} \approx 0$ °C to prevent freezing of the borehole heat extraction system. Water-water heat pump efficiency η^{ww} > brine-water heat pump efficiency η^{bw} at the same output temperature T_{warm}

Space heating: Thermal Response Test



- is a long-term in situ heat extraction or injection ex-periment involving the borehole heat exchanger
- yields average thermal conductivity along the borehole
- analysis of response test data often based on the infinite line source method

Long time approximation ($\kappa t/ r^2 >> 1$) for T ($r=r_b$) at the borehole wall:

$$T(r_b,t) \approx \frac{Q}{4\pi\bar{\lambda}}\left[\ln\left(4\kappa t/r_b^2\right)-\gamma\right]+Q\,R_b+T_0$$

(Q (in W m^{-1}) specific cooling/heating rate; r: radius; κ: thermal rock diffusivity; R_b: borehole thermal resistance; T_0: undisturbed temperature; γ≈0.5772 Euler's constant). Maximum error: 2.5 % and 10 % for κ t/ r-2 ≥ 20 and 5, respectively.

Expanding the logarithm's argument by t*/t* (t*: time unit) and collecting terms, this yields:

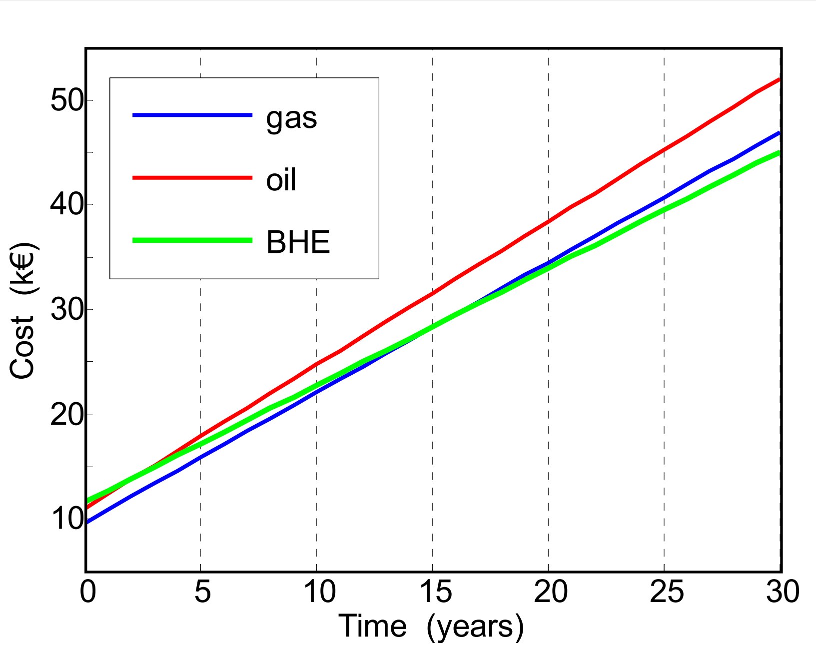
$$\bar{T}(t) = a\ln(t/t^*)+b,\ \text{where } a=\frac{Q}{4\pi\bar{\lambda}};\ b=Q\left(R_b+\frac{\ln\left(4\kappa t^*/r_b^2\right)-\gamma}{4\pi\bar{\lambda}}\right)+T_0.$$

Space heating: Earth coupled heat extraction

In heating and cooling modes, **maximum coefficients of performance** of modern **brine-water heat pumps** are **4 < COP_h < 5** and **3 < COP_c < 4**, respectively.

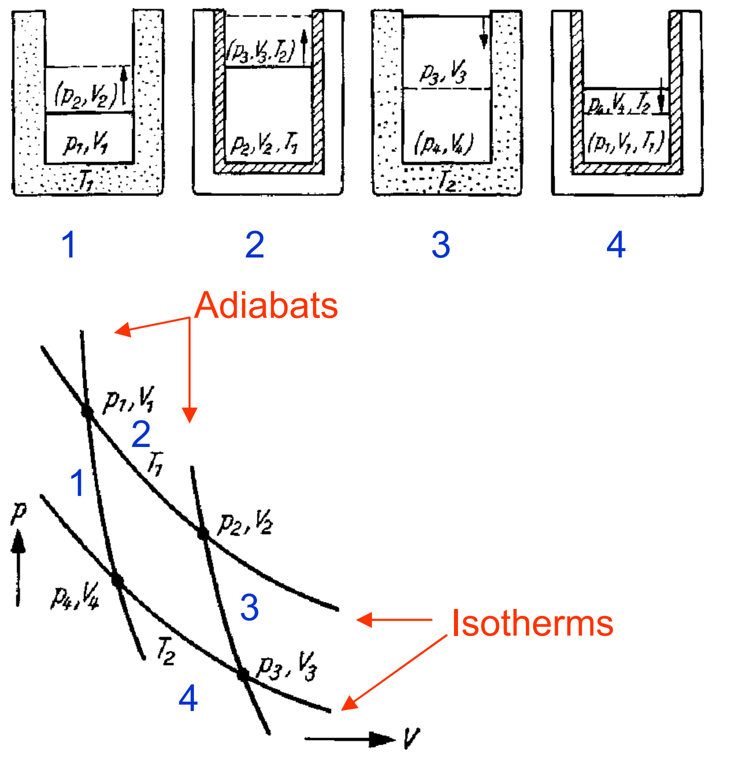
For **water-water heat pumps** corresponding ranges are **5 < COP_h < 6** and **4 < COP_c < 5**.

Thus, always more primary energy is produced than consumed, given a thermodynamic efficiency η between $0.3 \leq \eta \leq 0.4$ for the conversion of primary energy (e.g. coal, hydrocarbons) into electricity.

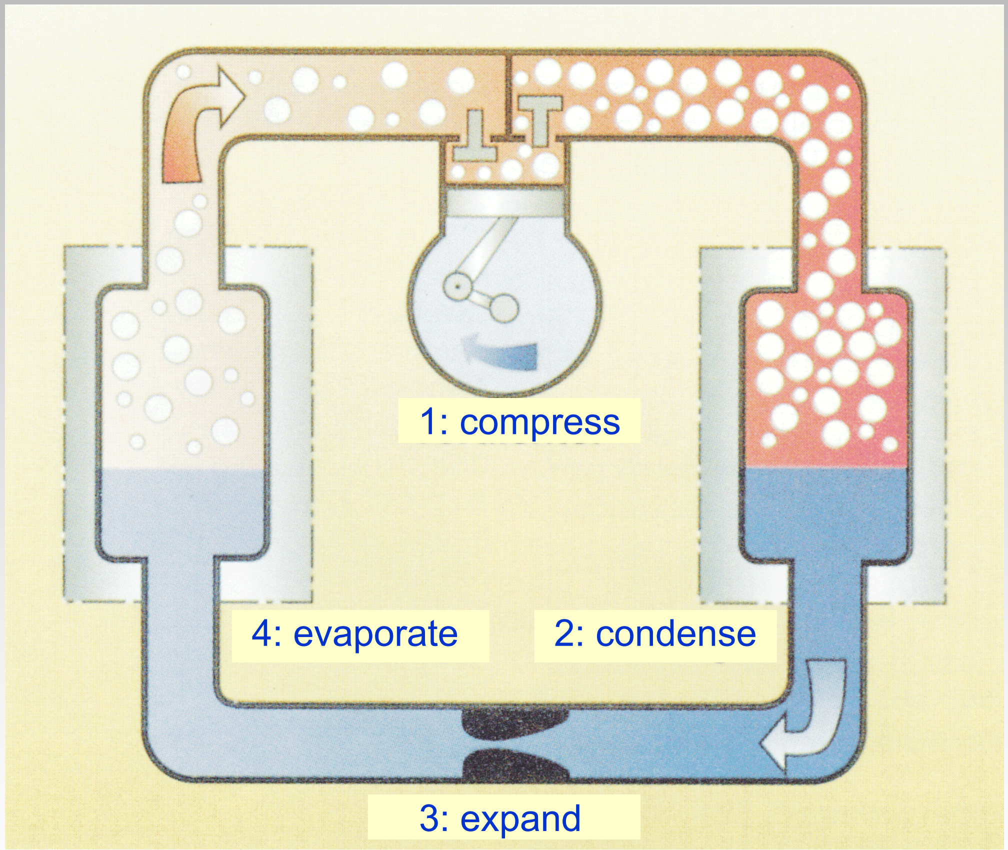


Example for heating cost comparison of a typical single family home (150 m²) based on oil and gas furnaces or borehole heat exchangers (BHE) in hard or soft rock (German year 2007 prices)

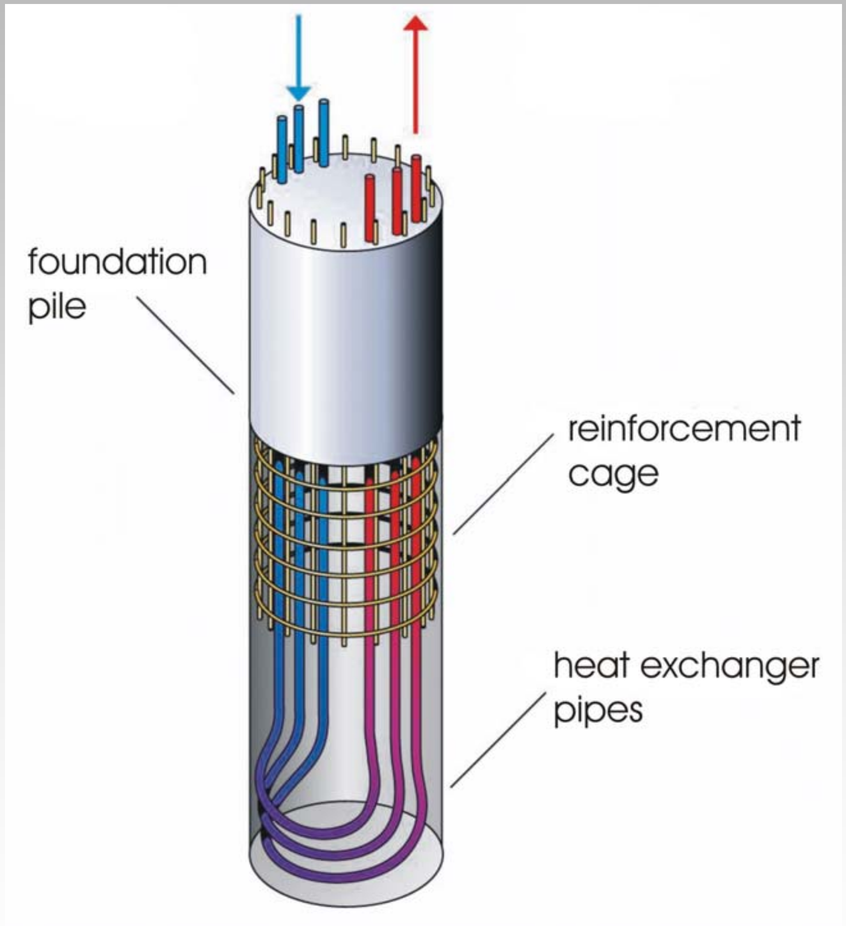
Heat pump and Carnot cycle



The thermodynamic Carnot cycle.



Space heating: Heat exchanger piles



von der Hude and Wend, 2004

Heat exchanger pipe systems integrated directly into concrete foundations of buildings and other constructions for heating and cooling. **Installed power**: 10 kW – 800 kW for small houses and large industrial buildings, respectively. Systems are usually connected to a heat pump.

Specific power (per meter of foundation pile) depends on temperature difference between inflow and outflow of the heat exchange fluid, ground thermal properties, amount of heat advection with groundwater flow: **20 W m^{-1} – 75 W m^{-1}** depending on local conditions and pile diameter.

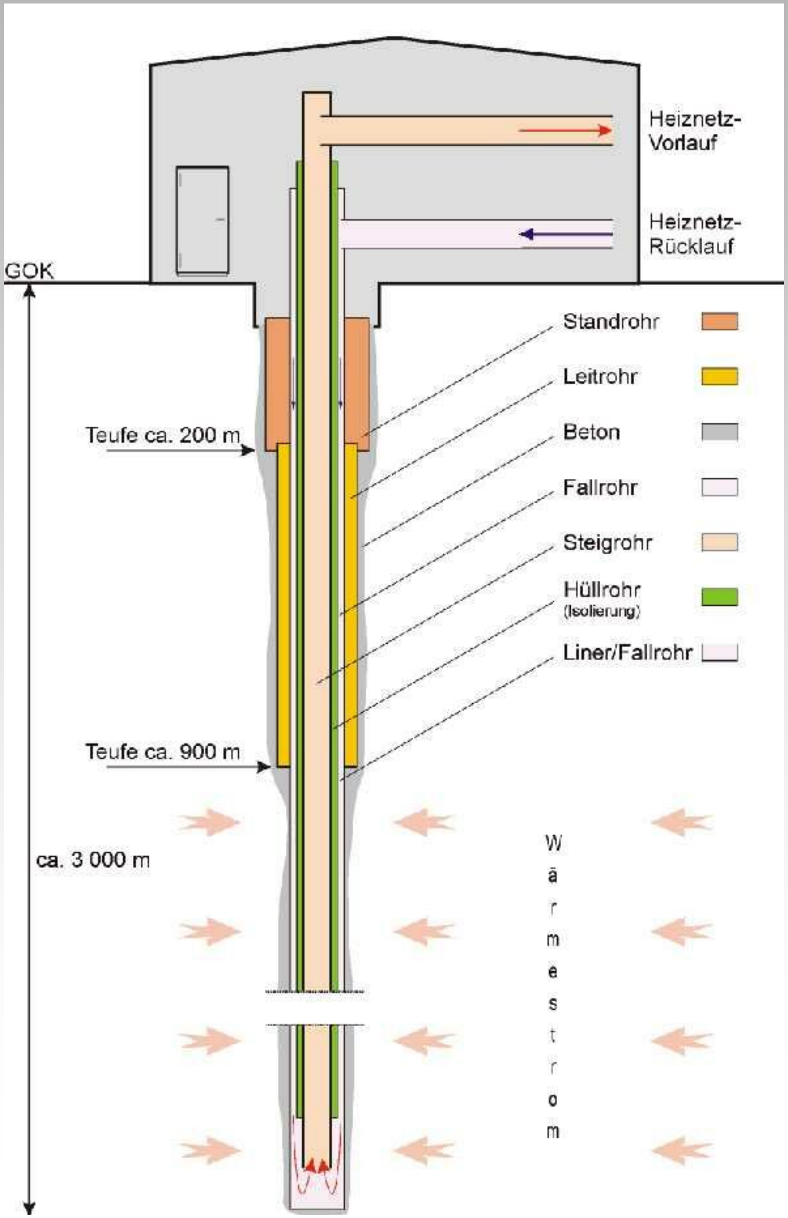
Space heating: Heat exchanger piles

Similar types of heat exchangers also integrated in concrete floors, ceilings and walls. Combined use of these different types of heat exchangers recently realized in Vienna for heating and cooling of a subway station: maximum **specific power per square meter** of heat exchange surface of all systems: **> 40 W m^{-2}**. Annual average specific power accordingly lower: **~13 W m^{-2}**. Average annual **heating and cooling energy: 170 MW h and 120 MW h**, respectively.

Large new terminal building of Zürich airport is heated and cooled with heat exchanger piles integrated in 315 foundation pillars of 30 m length and diameters of 0.9 m – 1.5 m. **Heating and cooling energy** is **470 MW h and 1100 MW h**, respectively.

Few statistical data on this type of direct use: for Switzerland 7 MW of installed power are reported by the year 2004. Significant potential: By the end of the **year 2002, more than 380 such systems** were reported to have been in operation in Austria, Germany, and Switzerland.

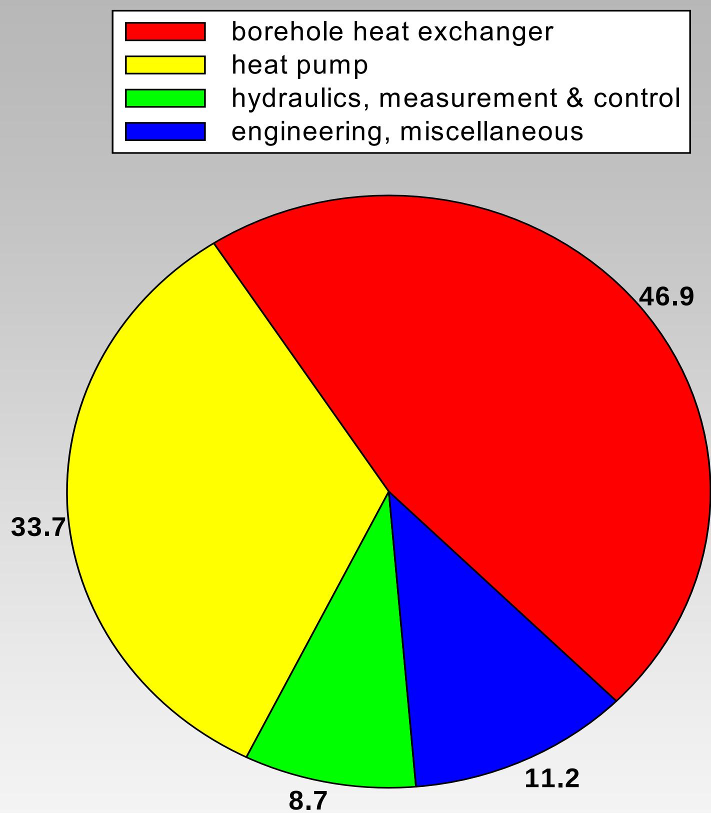
Space heating: Deep borehole heat exchangers

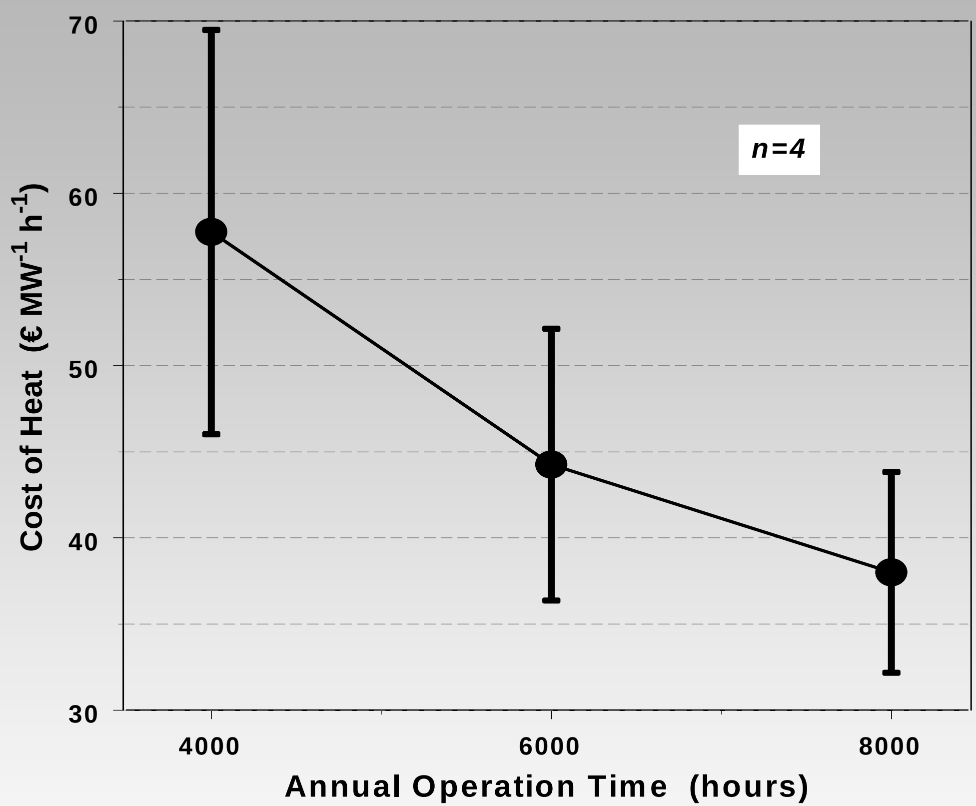


Depth: 1500 m – 3000 m; maximum temperatures: 60 °C – 110 °C. Coaxial arrangement of inner production pipe in an outer borehole casing. Production pipe often insulated Available operational data from small number of operating systems indicate **specific power** of about **20 W m^{-1} – 54 W m^{-1}**. Detailed numerical simulations calibrated on operational data from existing system indicates possible specific power of **85 W m^{-1}** for a 2300 m deep system, equal to **installed power** of about **200 kW**.

No heat pumps required and no cooling possible because of elevated output temperature.

Space heating: Deep borehole heat exchangers



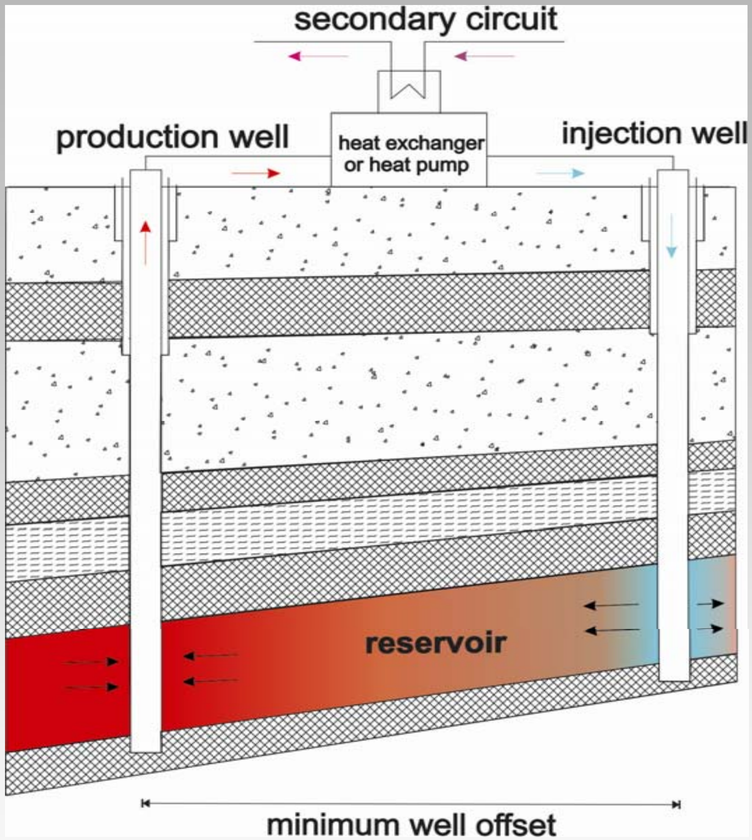


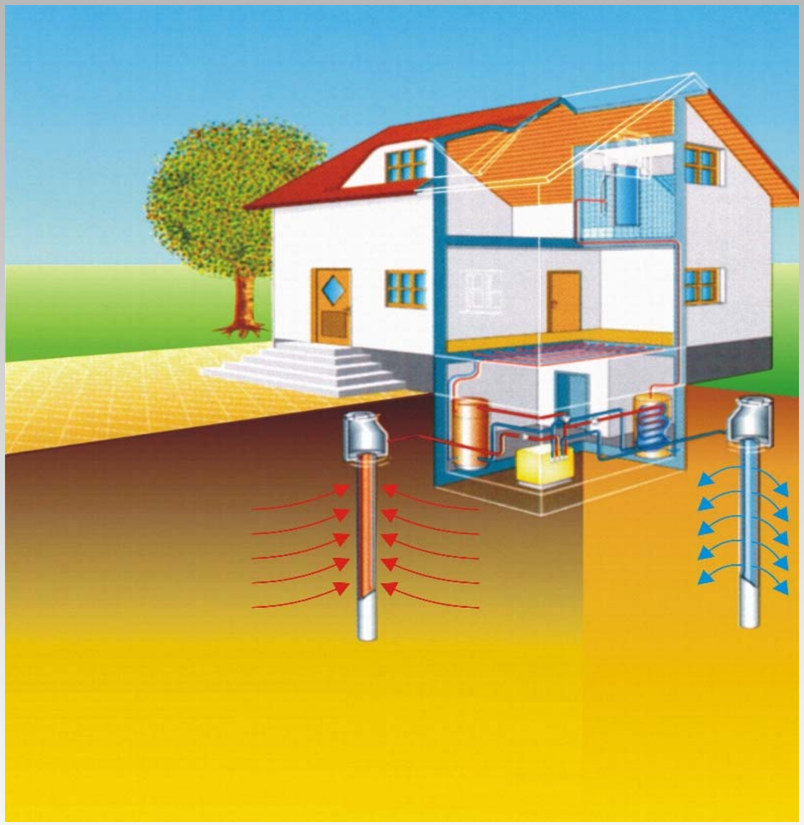
Left: Relative cost factors for deep bore-hole heat exchanger systems (depth 2500 m, German year 2002 prices)

Right: Mean and standard deviations of average cost for deep borehole heat exchanger systems (four different scenarios, German year 2002 prices).

Gas heating (German year 2007 prices): **40 € - 54 € per MW h**

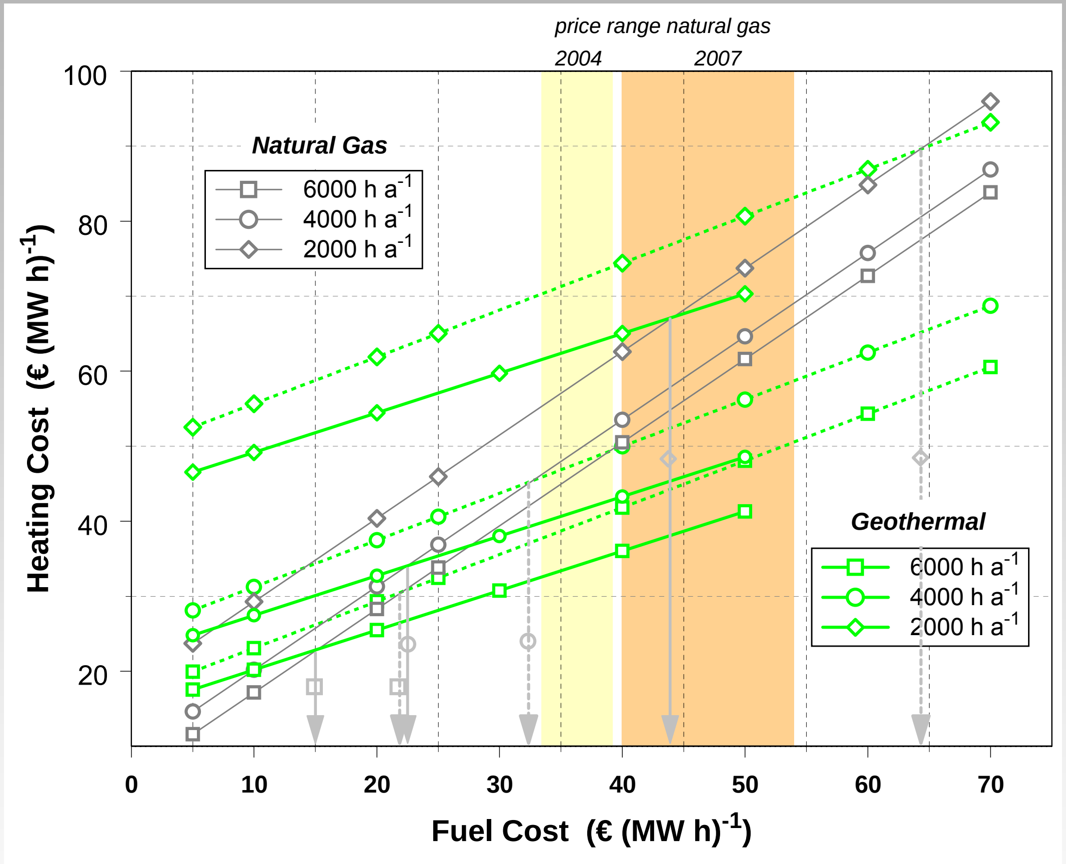
Space heating: Hydrothermal heating systems



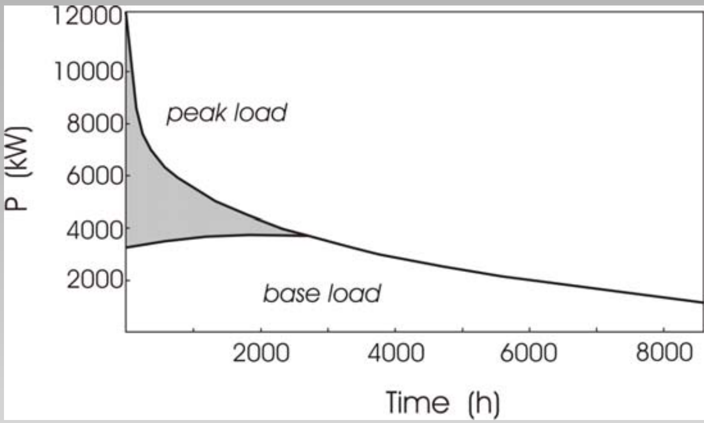


Hydrothermal doublet installations: heating plant (left), groundwater heat pump system (right). Advective heat mining requires production of large volumes of hot fluid. Hydraulic permeability is most critical reservoir property. Therefore, almost all hydrothermal heating systems are placed in sedimentary rocks, often in sedimentary basins.

Space heating: Hydrothermal heating systems



Modifiziert nach Schaumann, 2002



Top: Typical annual time-variation curve of heating power P versus time (one year equals 8760 hours)

Left: Heating cost for natural gas (11.2 MW_t) and geothermal heat with heat pumps of 11.2 MW_t and 11.4 MW_t with and without direct heat exchange (full and broken green lines, respectively). Solid and broken light gray arrows: break-even cost for geothermal heat with respect to fossil fuel for heat pumps with and without direct heat exchange of 2.1 MW_t, respectively. Light and dark brown shading: German large-consumer natural gas price ranges for 2004 and 2007.

Commercial and industrial direct applications

Largest current **industrial applications** in pulp, paper and wood processing: timber processing (New Zealand), diatomaceous earth plant (Iceland), vegetable dehydration plant (USA), industrial water (Romania).

Other applications currently operating or studied for feasibility:

- **Hydrogen production** by high-T steam hydrolysis (800 °C – 1000 °C)
- **hot-dip galvanizing** of metals (a chemical process used to coat steel or iron with zinc in a zinc bath (450 °C);
- **diatomite** (kieselgur) **production** (steam for heating and drying);
- **salt production** from seawater (steam for evaporation and drying);
- **timber drying**;
- **seaweed and kelp processing** (hot water, ~110 °C);
- **fat-liquoring and drying** in the tanning process of leather; fat-liquoring is introducing oil into the skin prior to drying to replace the natural oils lost during processing (~ 60 °C – 66 °C);
- thermal distillation **desalination** (52°C – 76 °C);
- **washing** in wool mills **and dyeing** cloth (48 °C – 79 °C);
- **production of chemicals** from geothermal brines.

Commercial and industrial direct applications

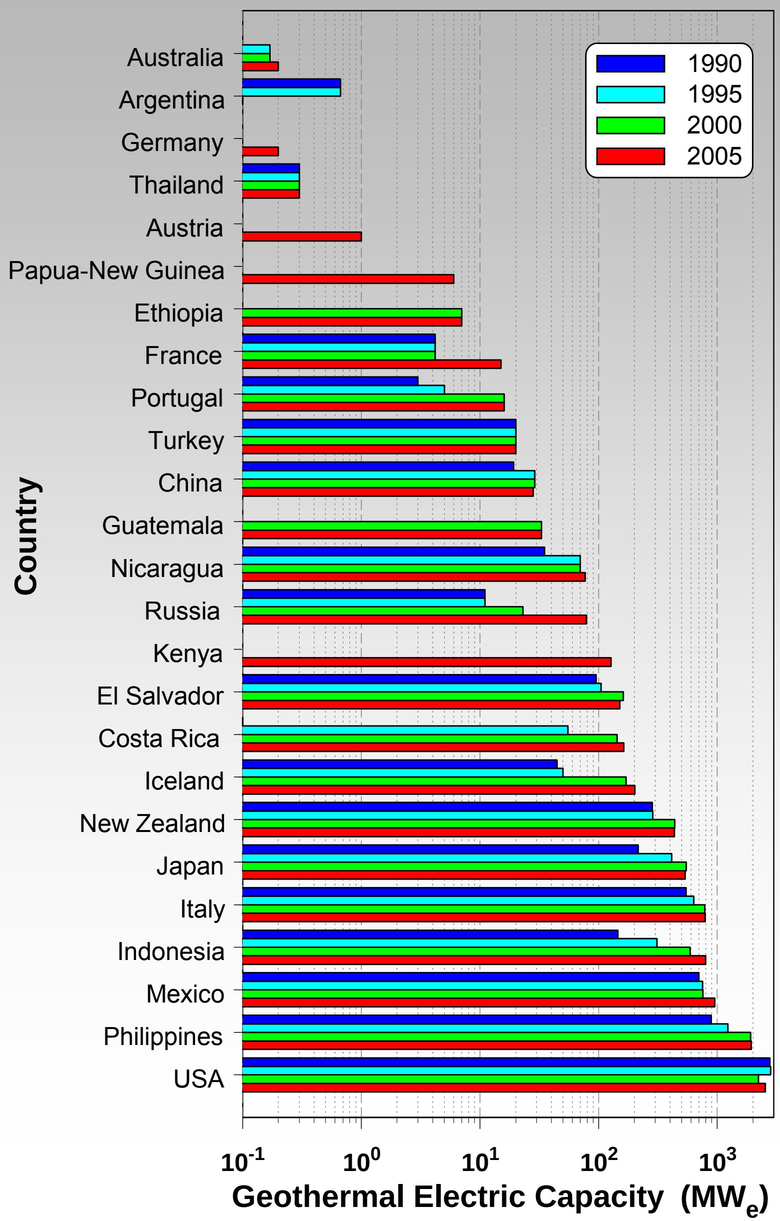
T (°C)	Process
180	evaporation of highly concentrated solutions; refrigeration by ammonia absorption; digestion in paper pulp
170	heavy water via hydrogen sulfide process; drying of diatomaceous earth; digestion of paper pulp
160	drying of fish meal; drying of timber
150	alumina via Bayer's process
140	drying farm products at high rates; canning of food
130	evaporation in sugar refining; extraction of salts by evaporation and crystallization; fresh water by distillation
120	most multi-effect evaporation; concentration of saline solution
110	drying and curing of light aggregate cement slabs
100	drying of organic materials. seaweed, grass. vegetables etc.; washing and drying of wool
90	drying of stock fish; intense de-icing operations
80	space-heating (buildings and greenhouses)
70	refrigeration (lower temperature limit)
60	animal husbandry; greenhouses by combined space and hotbed heating
50	mushroom growing; balneology
40	soil warming; swimming pools, biodegradation. fermentations
30	warm water for year-round mining in cold climates; de-icing; hatching of fish or turtles
20	fish farming

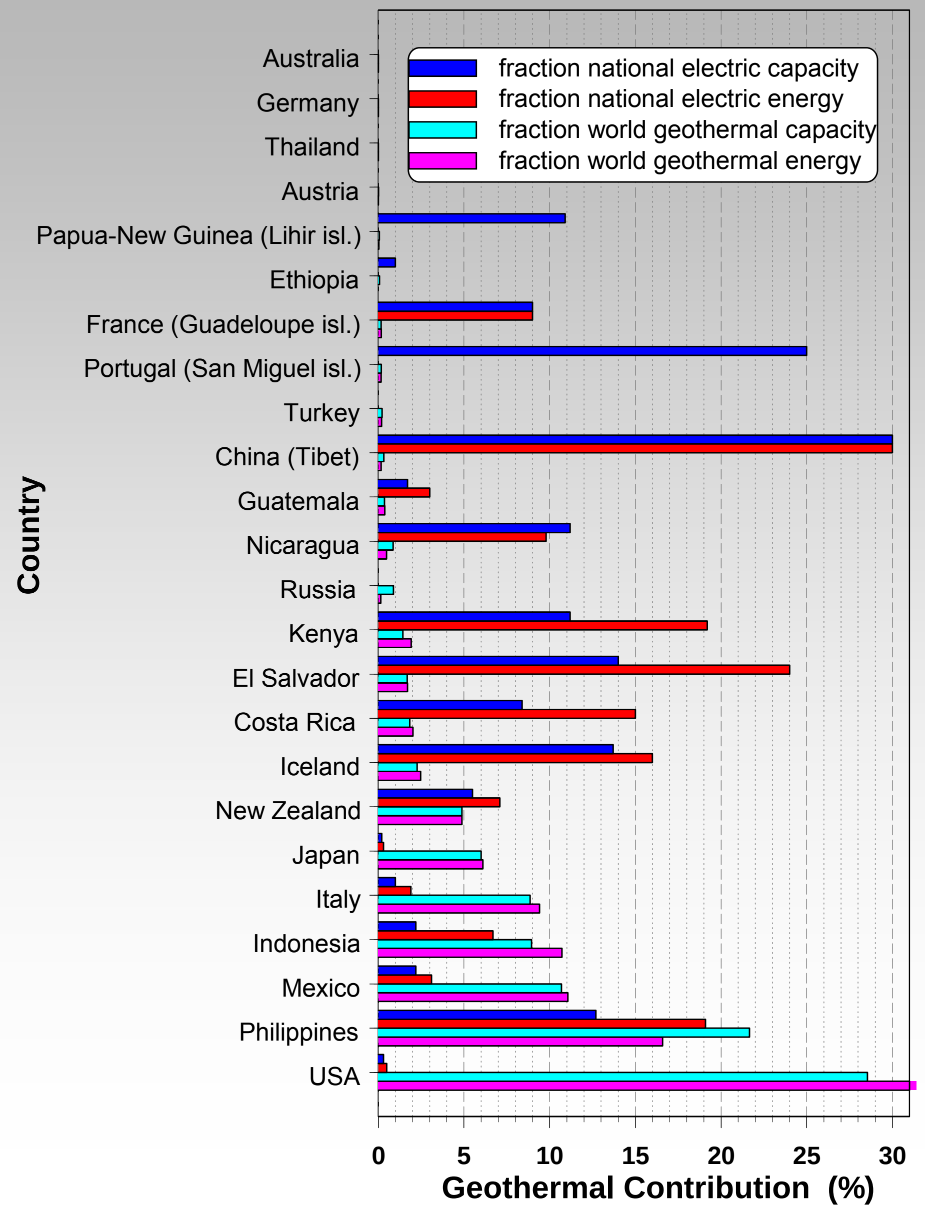
100 years of geothermal power generation

1904, Lardarello: five electric light bulbs powered by geothermal energy
1913, Lardarello: first industrial plant (**250 kW$_e$**)

2005, Lardarello: installed capacity **543 MW$_e$**
2005: 8912 MW$_e$ installed capacity **world-wide**;

Geothermal power generation 2005





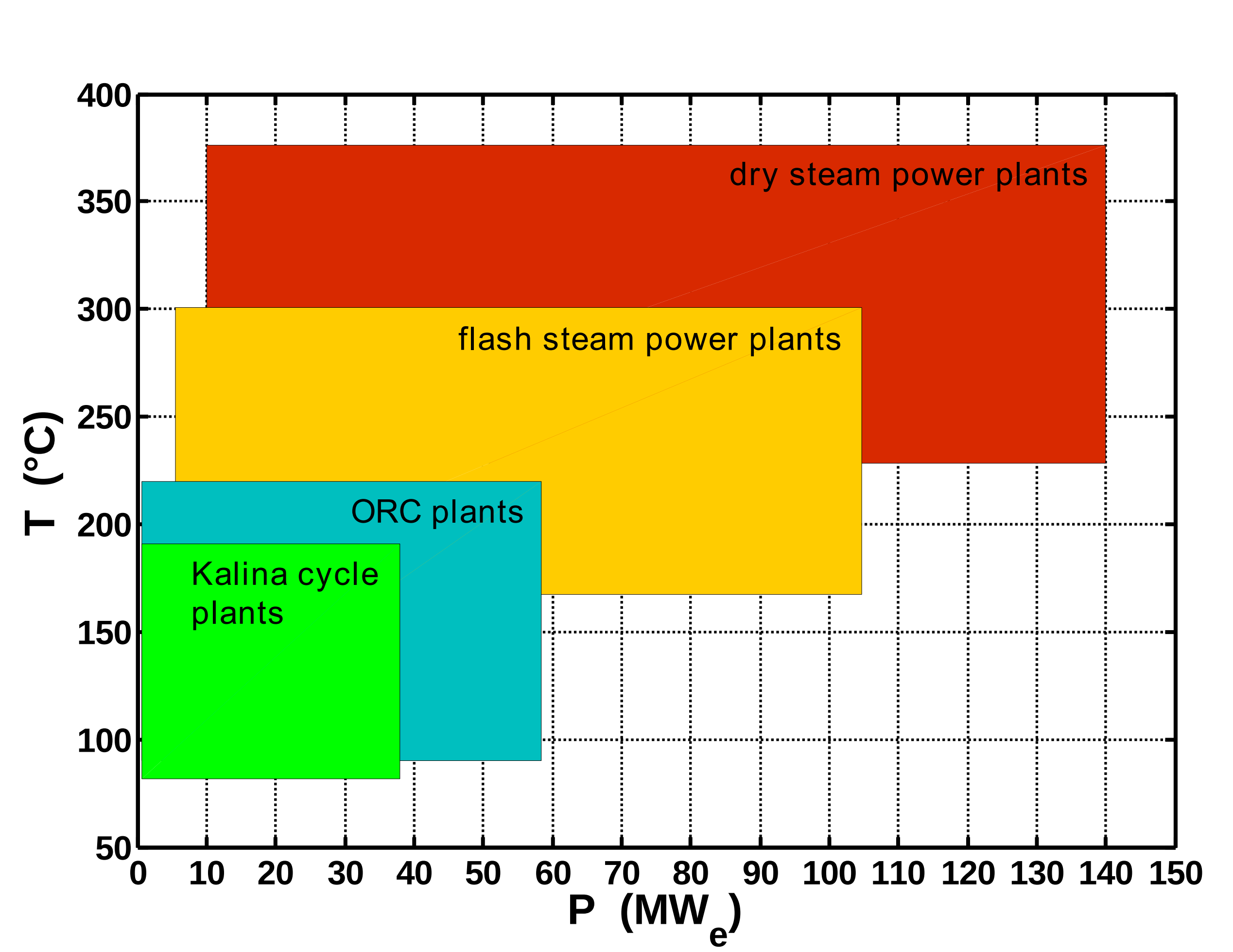
Geothermal power generation 2005

Country	Installed Capacity (MW)	Running Capacity (MW)	Energy (GW h a^{-1})	Number of Units	% National Capacity	% World Capacity	% National Energy	% World Energy
Australia	0.2	0.1	0.5	1	negligible	negligible	negligible	0.001
Austria	1	1	3.2	2	negligible	negligible	negligible	0.006
China	28	19	95.7	13	30.0 (Tibet)	0.314	30.0 (Tibet)	0.168
Costa Rica	**163**	**163**	**1145.0**	**5**	**8.4**	**1.829**	**15.0**	**2.016**
El Salvador	**151**	**119**	**967.0**	**5**	**14.0**	**1.694**	**24.0**	**1.703**
Ethiopia	7	7	–	1	1.0	0.078	–	–
France	15	15	102.0	2	9.0 (Guadeloupe isl.)	0.168	9.0 (Guadeloupe isl.)	0.180
Germany	0.2	0.2	1.5	1	negligible	negligible	negligible	0.003
Guatemala	**33**	**29**	**212.0**	**8**	**1.7**	**0.370**	**3.0**	**0.373**
Iceland	**202**	**202**	**1406.0**	**19**	**13.7**	**2.267**	**16.0**	**2.475**
Indonesia	**797**	**838**	**6085.0**	**15**	**2.2**	**8.943**	**6.7**	**10.713**
Italy	**790**	**699**	**5340.0**	**32**	**1.0**	**8.864**	**1.9**	**9.402**
Japan	535	530	3467.0	19	0.2	6.003	0.3	6.104
Kenya	**127**	**127**	**1088.0**	**8**	**11.2**	**1.425**	**19.0**	**1.916**
Mexico	**953**	**953**	**6282.0**	**36**	**2.2**	**10.693**	**3.1**	**11.060**
New Zealand	**435**	**403**	**2774.0**	**33**	**5.5**	**4.881**	**7.1**	**4.884**
Nicaragua	**77**	**38**	**270.7**	**3**	**11.2**	**0.864**	**9.8**	**0.477**
Papua-New Guinea	6	6	17.0	1	10.9 (Lihir isl.)	0.067	–	0.0299
Philippines	**1931**	**1838**	**9419.0**	**57**	**12.7**	**21.667**	**19.1**	**16.58**
Portugal	16	13	90.0	5	25.0 (San Miguel isl.)	0.179	–	0.158
Russia	79	79	85.0	11	negligible	0.886	negligible	0.150
Thailand	0.3	0.3	1.8	1	negligible	0.003	negligible	0.003
Turkey	20	18	105.0	1	negligible	0.224	negligible	0.185
USA	2544	1914	17840.0	189	0.3	28.546	0.5	31.410
TOTAL	***8912***	***8010***	***56798.0 (204.4 PJ)***	***468***	–	***100.000***	–	***100.000***

Geothermal power generation

- Vapor required to drive turbines for generating electric power, in general natural **dry or wet, medium to high enthalpy steam at temperatures above 150 °C**.
- Binary systems employing substances with a lower boiling point than water in a secondary circuit used to generate vapor for driving turbines at **lower temperatures**: **Organic Rankine Cycle** (ORC) or **Kalina Cycle**. Used for low to moderate temperature, water dominated reservoirs.
- Engineered **Hot Dry Rock** (HDR) or **Enhanced Geothermal Systems** (EGS) in absence of natural steam or hot water reservoirs, or for insufficiently permeable reservoirs.
- Geothermal power plants **can be built** economically in much **smaller** units than e.g. hydropower stations. Units range from **15 MW_e – 30 MW_e**: capacity of geothermal power plants can be adjusted more easily to growing demand for electric power in developing countries with relatively small electricity markets than hydropower plants (unit size: 100 MW_e – 200 MW_e).
- Geothermal power plants: **very reliable**, with annual load and availability factors of commonly around 90 %; **little affected by external factors** (e.g. seasonal variations in rainfall).

Geothermal power generation



Power range and characteristic reservoir temperatures for generation of electric power by direct-intake dry steam plants, single or multiple flash wet steam plants, ORC and Kalina cycle hot water plants

Dry steam systems

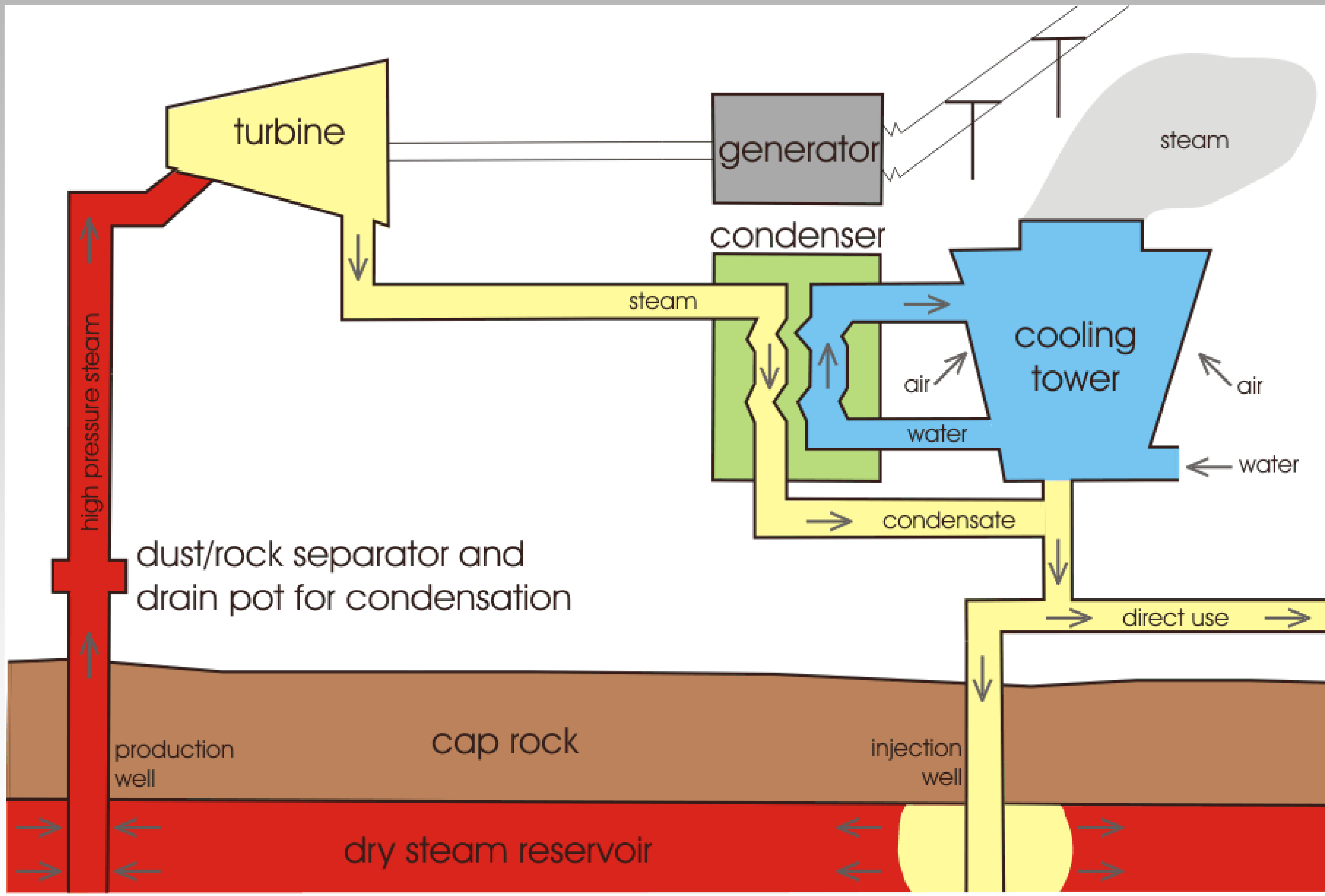
Direct, non condensing cycle plants: **15 kg – 25 kg of steam per kW h_e** generated electricity; only alternative if non-condensable gases exceed 50 weight % of steam; generally preferred over condensing cycles if non-condensable gases exceed 15 weight % of steam, because removal from the condenser consumes power and reduces plant efficiency.

Condensing plants: steam condensed at turbine outlet and cooled in conventional cooling towers. Condensing steam at turbine exhaust creates vacuum of about 150 hPa (< 15 % atmospheric pressure), thus maximizing the pressure drop across turbine and hence power output. Thus, condensing plants require ~50 % less steam than non-condensing ones, only **6 kg – 10 kg of steam per kW h_e** generated, but steam may not contain more than 15 % non-con-densable gases.

Specific steam consumption depends on turbine inlet pressure: **6 kg of steam per kW h_e at 1.5 MPa – 2.0 MPa; 9 kg – 7 kg of steam per kW h_e at 0.5 –1.5 MPa** ; much more for even lower pressures.

Steam piped directly from the wells into turbine; well developed, commercially available technology. **Capacities of typical turbine units: 20 MW_e –120 MW_e**; modular standard units of 20 MW_e also available

Direct-intake, condensing plant



For heat mining of dry steam fields

Dry steam systems

Lardarello, Italy (543 MW)
(dry steam)

The Geysers, USA (888 MW)
(dry steam)

Pico Vermelho, Azores
(direct-intake, dry steam)

Kamojang, Indonesia (140 MW)
(dry steam)

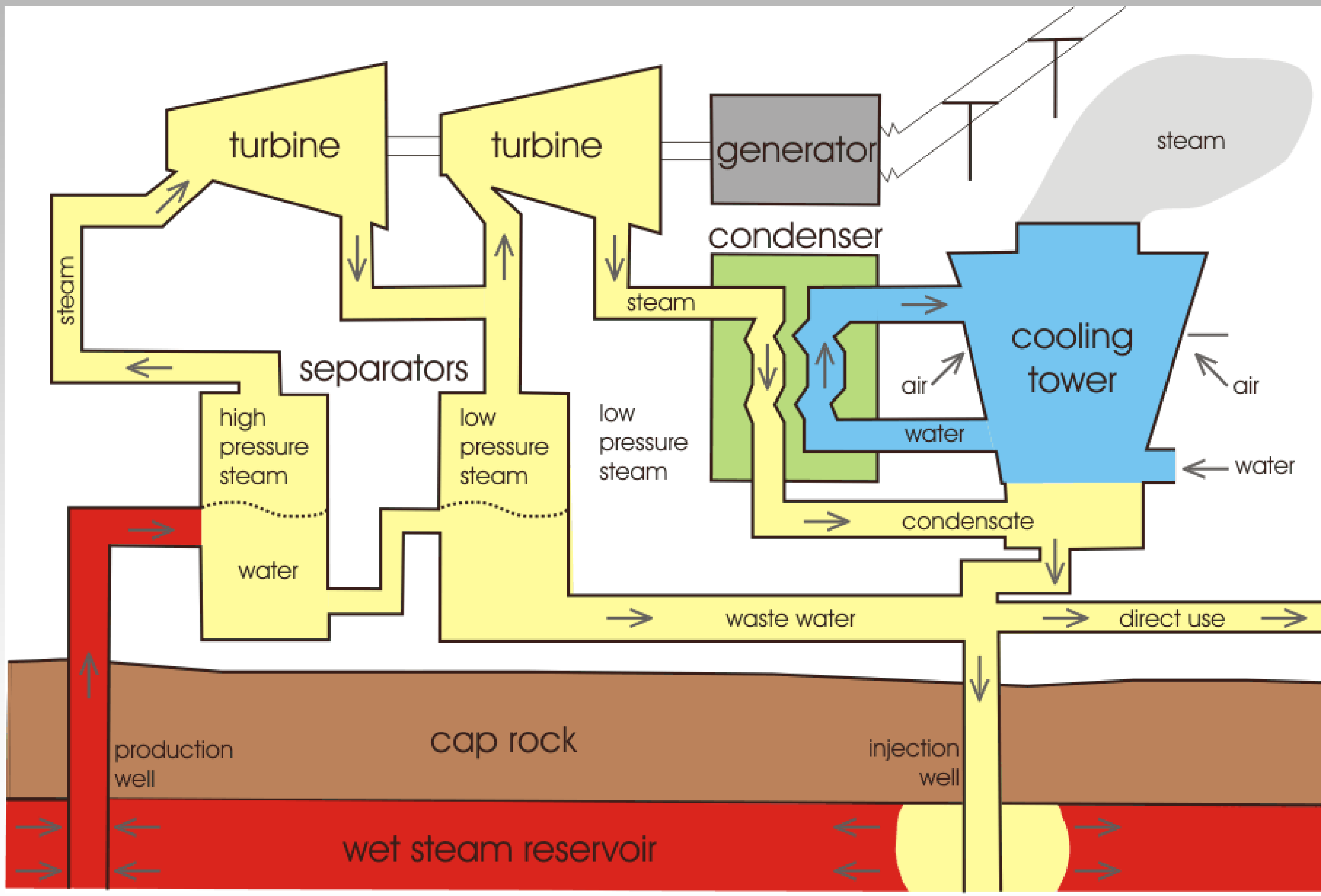
Wet steam systems

Flash Steam Power Plants: water dominated, wet steam reservoirs; much more common than vapor dominated ones. Most of high-temperature geothermal resource provided by pressurized water. Fields often indicated by **boiling springs and geysers**. Large heat source, generally magmatic origin, forming a hydrothermal resource.

When a well penetrates a reservoir, the pressurized water flows into well: **some liquid water evaporates** due to pressure drop, and **well co-produces hot water** (the dominant phase) **and steam** ("wet steam fields"). Water-steam ratio varies from field to field and even within same field.

Often large load of **dissolved minerals (10^{-3} – 10^{-1} kg$_{mineral}$ per kg$_{fluid}$**, in some fields up to 0.35 kg/kg), mainly chlorides, bicarbonates, sulfates, borates, fluorides, and silica; can cause severe scaling in pipelines and plants. Large quantity of brines produced with the steam (e.g. 6600 t h^{-1} at Cerro Prieto, Mexico) an important economic aspect in exploiting wet steam fields, requiring reinjection into reservoir.

Double flash, condensing plant



For heat mining of wet steam fields

Wet steam systems

Wet steam cannot be fed to standard turbines without risk of damage to the turbine blades; requires separating steam from water:

Single or multiple flash steam plants used to produce energy from these fields by evaporating depressurized liquid water into steam in one or several separators at the surface. **Single, double-, and triple flash** systems are used. Commercially available turbo-generator units are commonly in the range 10 MW_e – 55 MW_e; modular standard generating units of 20 MW_e also used.

Wet steam systems

Matsukawa, Japan (24 MW)
(wet steam)

Imperial Valley, USA
(wet steam, double flash)

Wairakei, New Zealand (wet steam, triple flash)

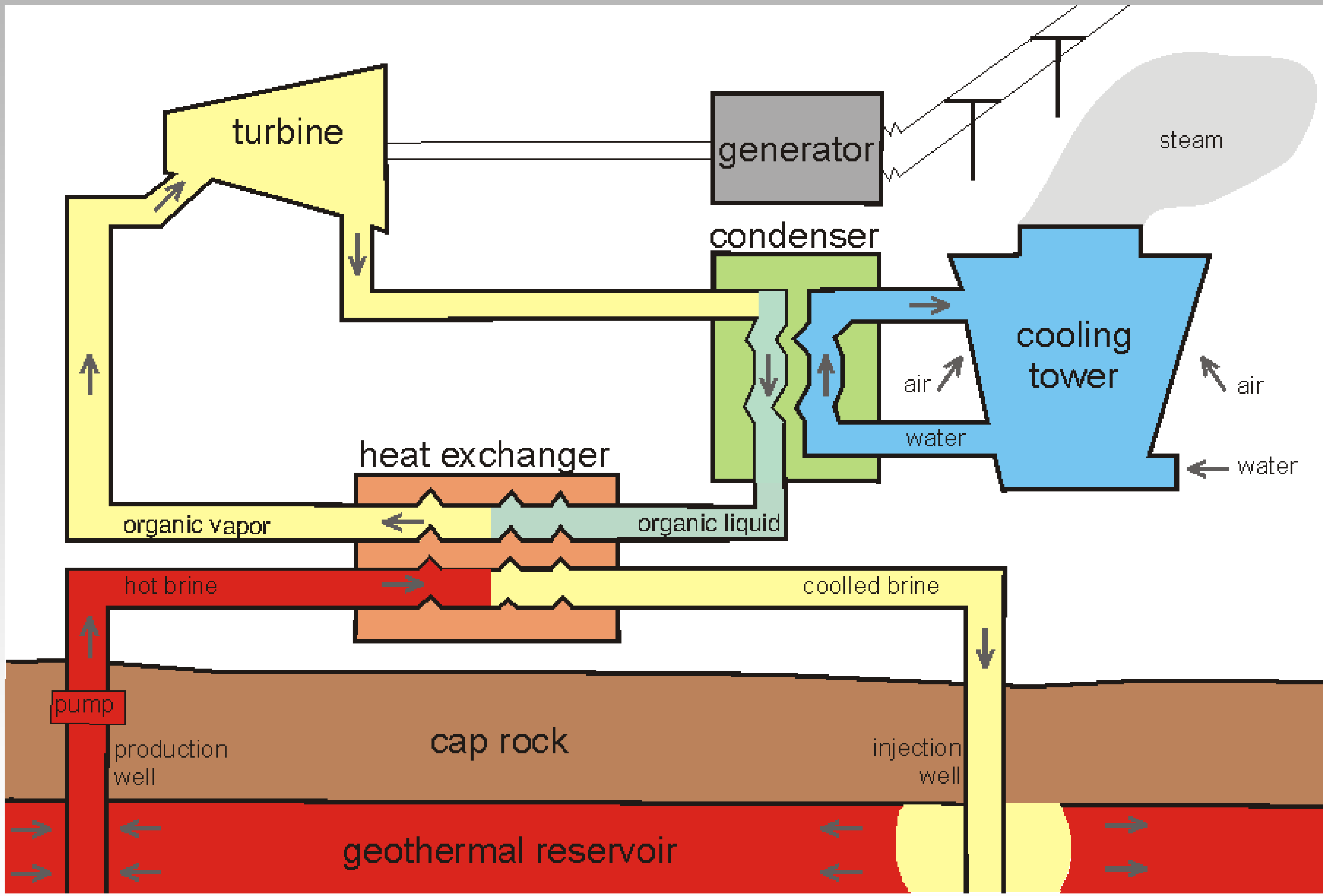
Binary systems

Binary power plants allow to convert geothermal heat from low enthalpy, water dominated **hot water reservoirs** into electricity, provided reservoir temperatures exceed 85 °C.

Also well suited to exploit **medium enthalpy wet steam resources** with high water-to-steam ratios at temperatures lower than practical for flash steam systems. Binary plants convert medium-temperature resources into electricity more efficiently than other technologies.

Heat exchanger transfers heat from produced hot brine in primary loop to low boiling-point working fluid in secondary loop: thermodynamic cycle known as **Organic Rankine Cycle** (ORC): initially organic compounds were used as working fluid. Secondary loop working fluid evaporated in vaporizer by geothermal heat provided in primary loop. Vapor expands as it passes through organic vapor turbine coupled to generator. Exhaust vapor condensed in water-cooled condenser or air cooler and pumped to vaporizer. Binary cycle plants require **400 kg kW^{-1} h^{-1} of hot water** from low-to-medium enthalpy resources (**85 °C –150 °C**).

Binary plant



For heat mining of hot water or low enthalpy wet steam fields

Binary systems

Cooled brine can be discharged or reinjected into the reservoir without flashing, minimizing scaling problems.

Typical **unit size: 1 MW_e – 3 MW_e**. Binary power plant technology is **most cost-effective and reliable** way to convert large amounts of low temperature geothermal resources into electricity: **Large low-temperature reservoirs exist at accessible depths almost anywhere in the world**.

Power rating of geothermal turbine/generator units smaller than in conventional thermal power stations. Most common unit capacities are 55, 30, 15, 5 MW_e or smaller.

Binary systems

enable **decentralized geothermal power production** feasible with unit sizes of 0.1 MW_e – 100 MW_e;

economically attractive both in many remote or less developed regions of the world, but also in low enthalpy regions of developed countries where financial incentives promote low CO_2-emission energy production technologies, e.g. Germany's renewable energy act requiring grid operators to feed geothermal electric energy into their grids at a certified price:

Reimbursement for geothermal electric energy according to the German Renewable Energy Act (EEG)	
Installed capacity (MW)	**Reimbursement (€ kW^{-1} h^{-1})**
0 – 10	0.160
> 10	0.105
Before 2015	+ 0.040
Combined heat and power	+ 0.030
Petrothermal systems	+ 0.040

Binary and combined systems

Wendel Hot Springs, USA
(binary cycle, 700 kW)

Bad Blumau, Austria (250 kW)
(binary cycle)

Puna, Hawaii (30 MW)
(combined cycle)

Leyte, Philippines (125 MW)
(combined cycle)

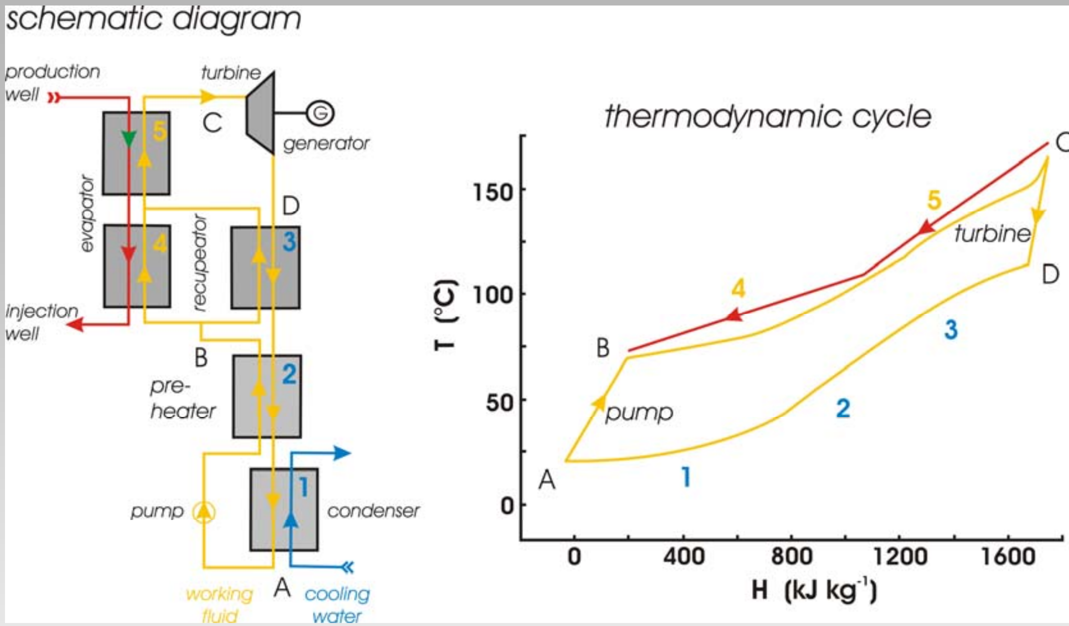
Kalina cycle

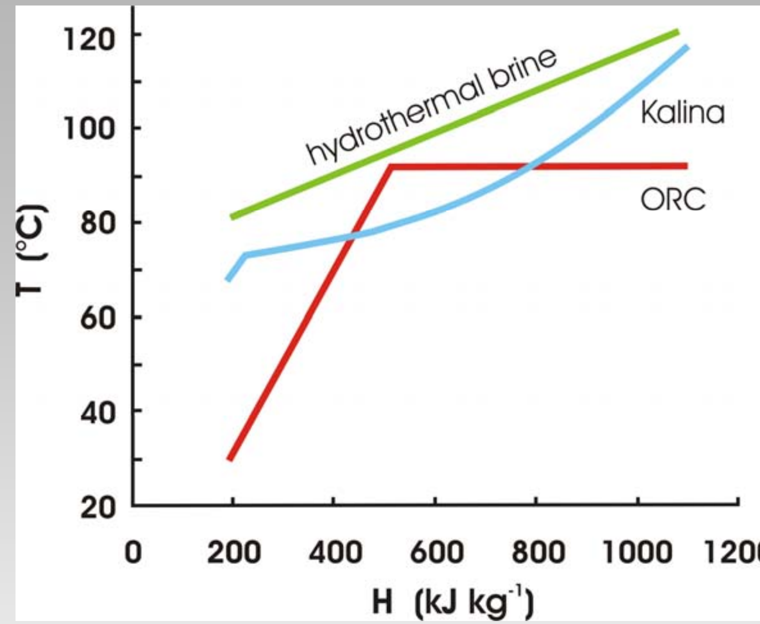
Binary power plant efficiency further improved by the Kalina Cycle technology: **Evaporation of water-ammonia** (NH_3) **mixture over finite temperature range**, producing two-component vapor (70 % ammonia and 30 % water). In contrast ORC process evaporates pure fluids at specific boiling temperatures.

Main thermodynamic advantage of Kalina over Organic Rankine cycle due to fact that the **water-ammonia mixture**, unlike pure fluids, **boils at a variable temperature**: working fluid temperature remains closer to that of hot brine in primary circuit, improving exergy efficiency by 10 % − 20 %.

Improved efficiency of Kalina over Organic Rankine cycle: Theoretical predictions: $\geq$ **10 %**. Recent comparison based on simulated identical conditions: **~3 %**.

Kalina cycle

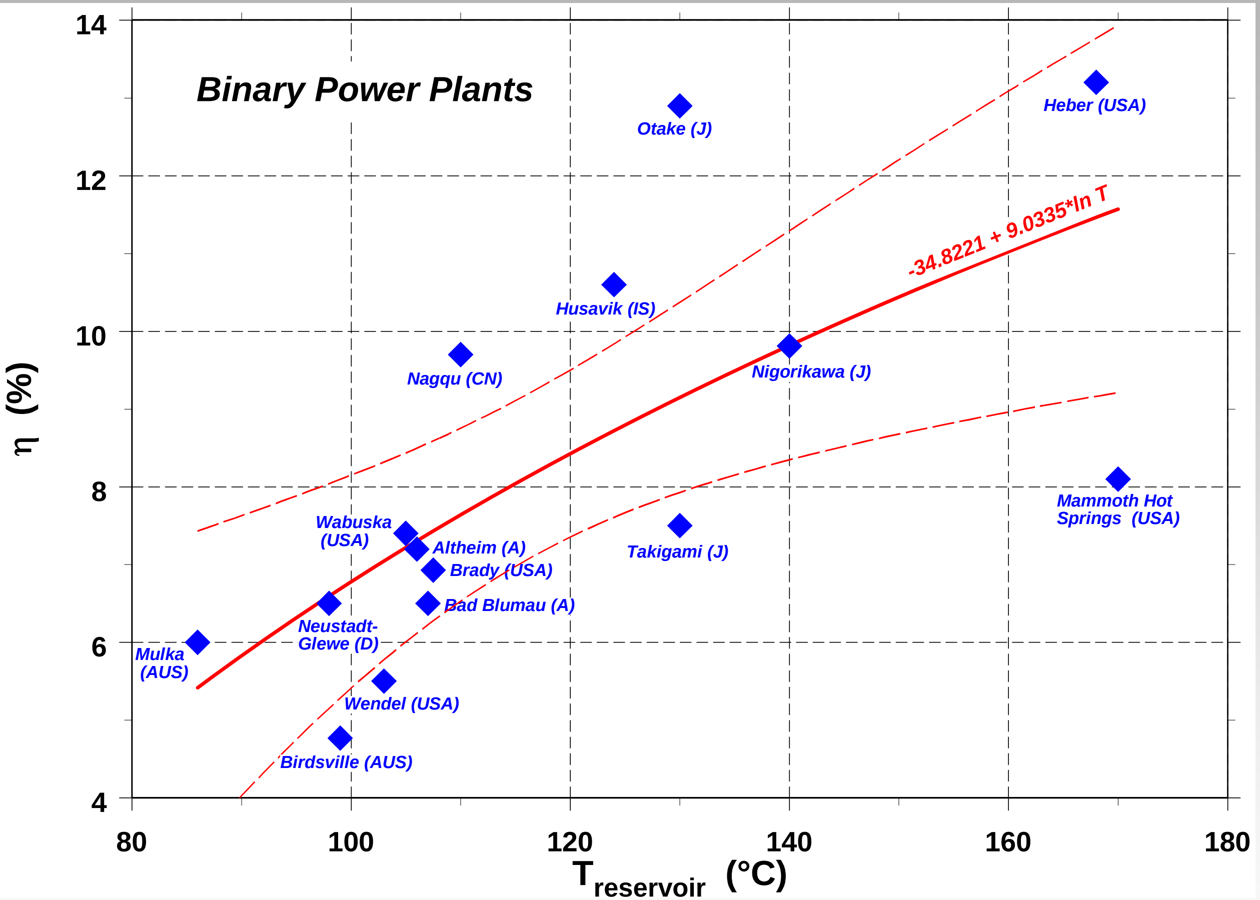




Left and center: Schematic diagram and thermodynamic cycle of the Kalina process showing temperature T versus enthalpy H. The temperature range in this example is 150 K, from 21 °C at point A to 171 °C at point C. Condensation (stages 1-3) at low ammonia concentration (40 % ammonia and 60 % water), evaporation (stages 4-5) at higher ammonia concentrations (70 % ammonia and 30 % water).

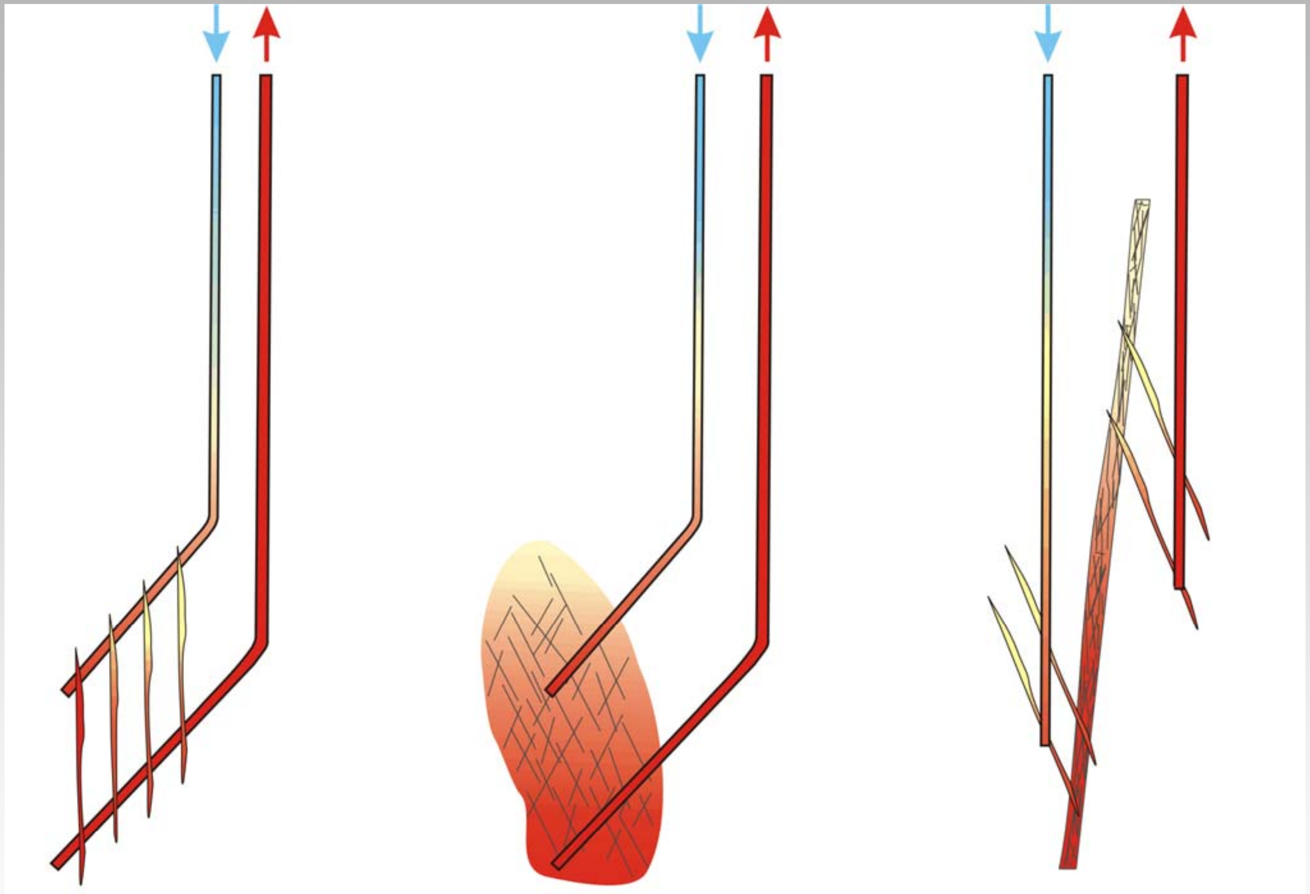
Right: Evaporation curves of working fluids in ORC and Kalina cycles, and hydrothermal brines showing temperature T versus enthalpy H.

Binary system efficiency



Net thermal efficiency η versus input reservoir temperature for various binary power plants (Husavik: Kalina cycle, all others: ORC). Full red line indicates logarithmic trend defined by nonlinear regression; broken red lines indicate 95 % confidence limits, (A: Austria, AUS: Australia, CN: People's Republic of China, D: Germany, Iceland: IS, J: Japan

Hot Dry Rock and Enhanced Geothermal Systems



(a) coin-shaped vertical cracks

(b) network of micro-cracks, fissures and fractures

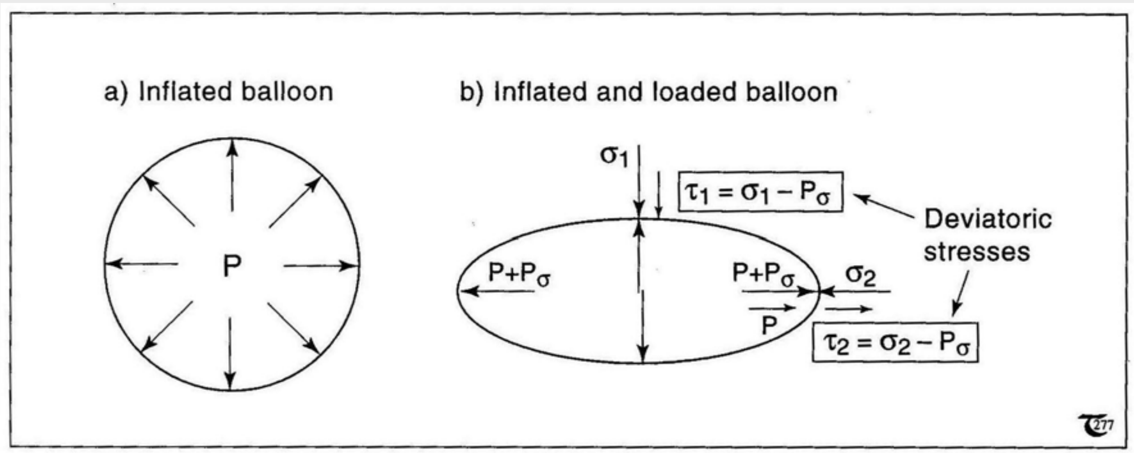
(c) interconnected large-scale fractures and faults

Different kinds of sub-surface heat exchanger systems in HDR and enhanced geothermal systems

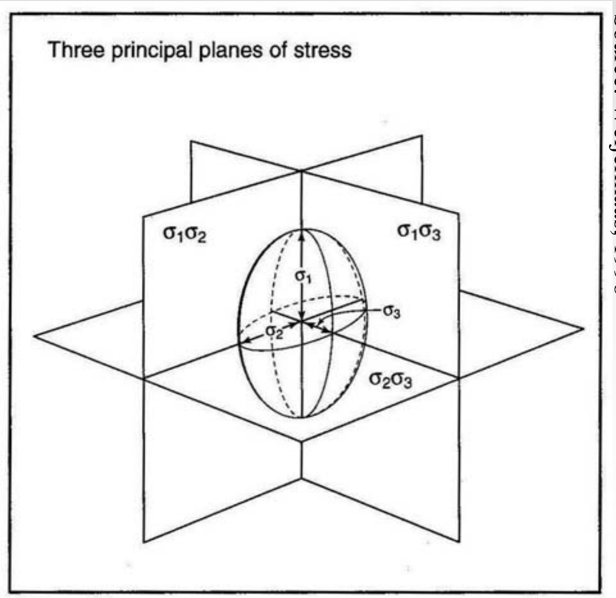
Stress in Rocks

- hydrostatic, or mean pressure P: $$P = \sigma_{mean} = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3}$$
- Principle stresses $\sigma_{1,2,3}$
- Deviatoric stresses $\tau_{1,2,3}$ $$\tau_{1,2,3} = \sigma_{1,2,3} - P$$

therefore: $\tau_1 = -\tau_3$



Source: Weijermaas, 1998



Source: Weijermaas, 1998

Mohr Equations

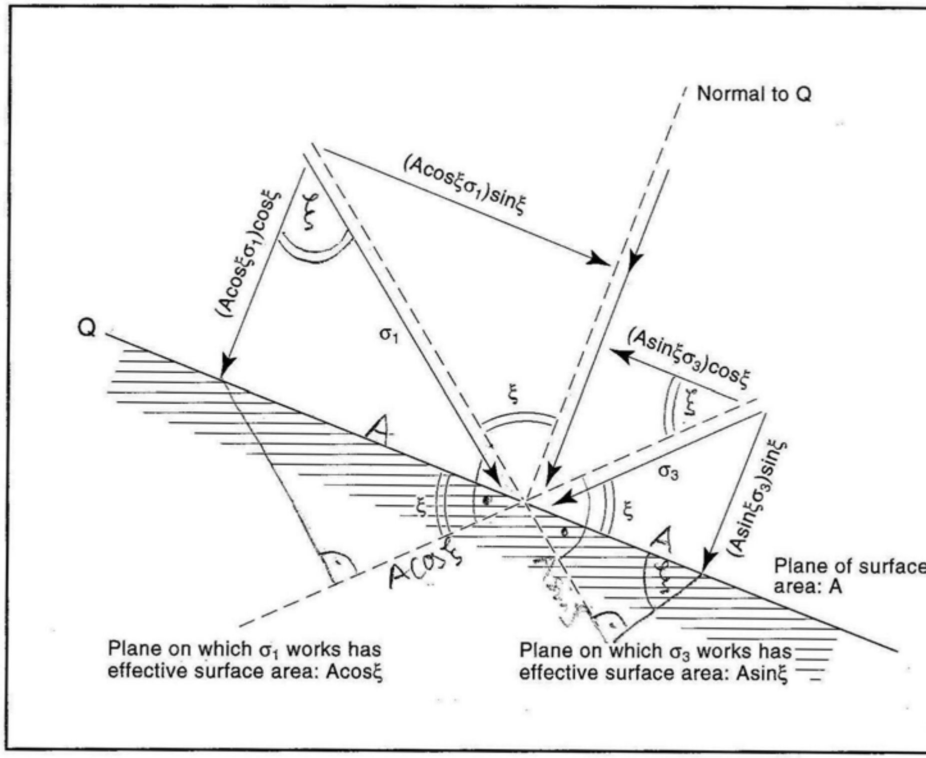
- Normal stress σ_N:
  $F_N=F_1\cos\xi+F_3\sin\xi$, thus:
  $\sigma_N A=(\sigma_1 A\cos\xi)\cos\xi+(\sigma_3 A\sin\xi)\sin\xi$
- Tangential stress σ_S:
  $F_S=F_1\sin\xi-F_3\cos\xi$, thus:
  $\sigma_S A=(\sigma_1 A\cos\xi)\sin\xi-(\sigma_3 A\sin\xi)\cos\xi$

$$\sigma_N=\frac{\sigma_1-\sigma_3}{2}\cos(2\xi)+\underbrace{\frac{\sigma_1+\sigma_3}{2}}_{P}$$

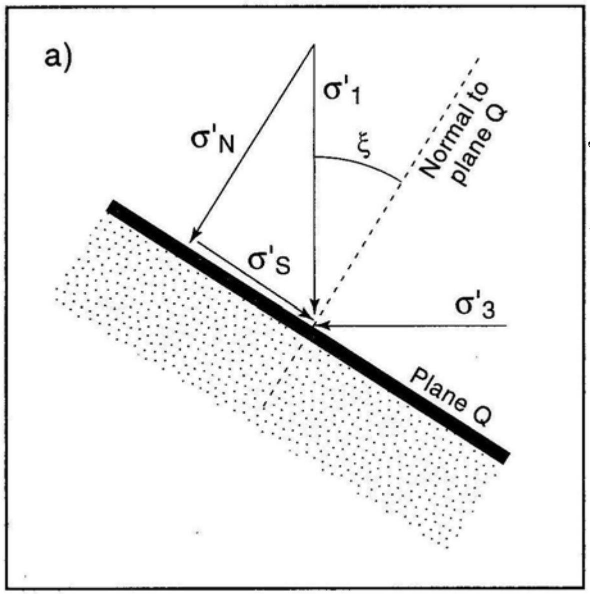
$$\sigma_S=\frac{\sigma_1-\sigma_3}{2}\sin(2\xi)$$

$$\tau_N=\tau_1\cos(2\xi)$$

$$\tau_S=\tau_1\sin(2\xi)$$



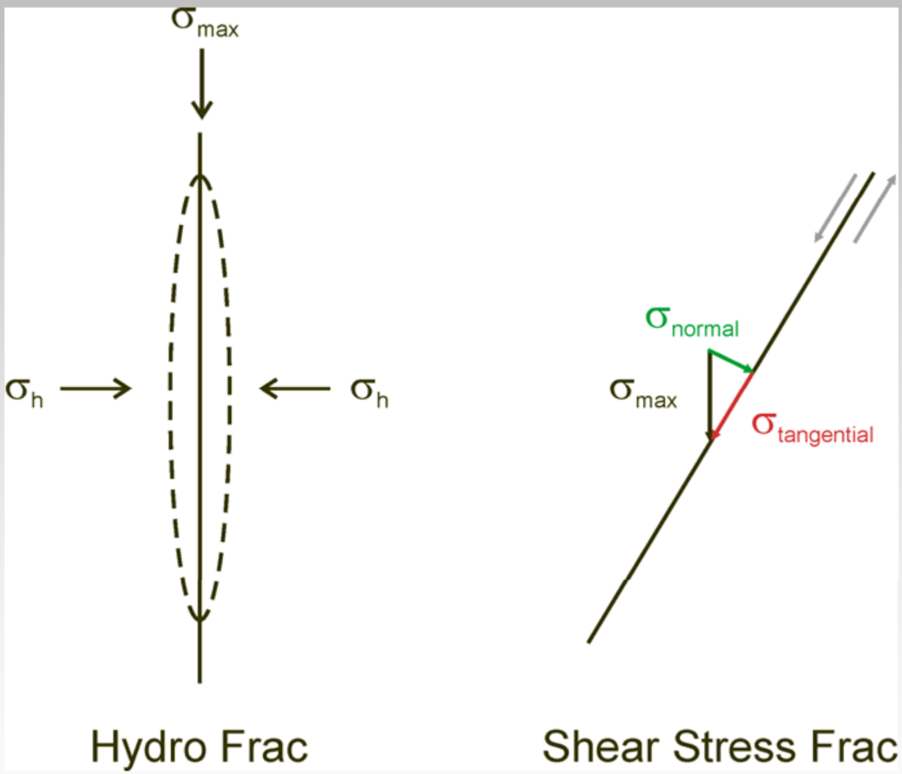
Source: Weijermaas, 1998



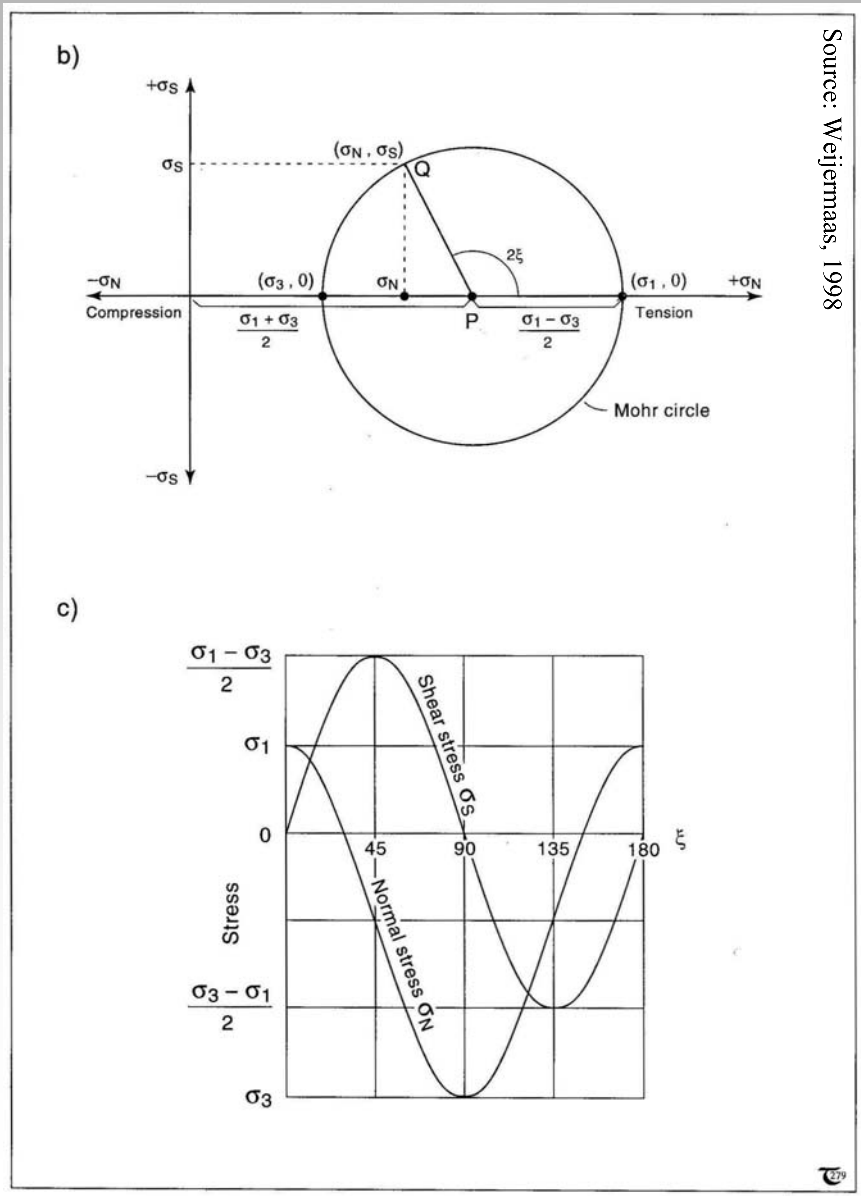
Source: Weijermaas, 1998

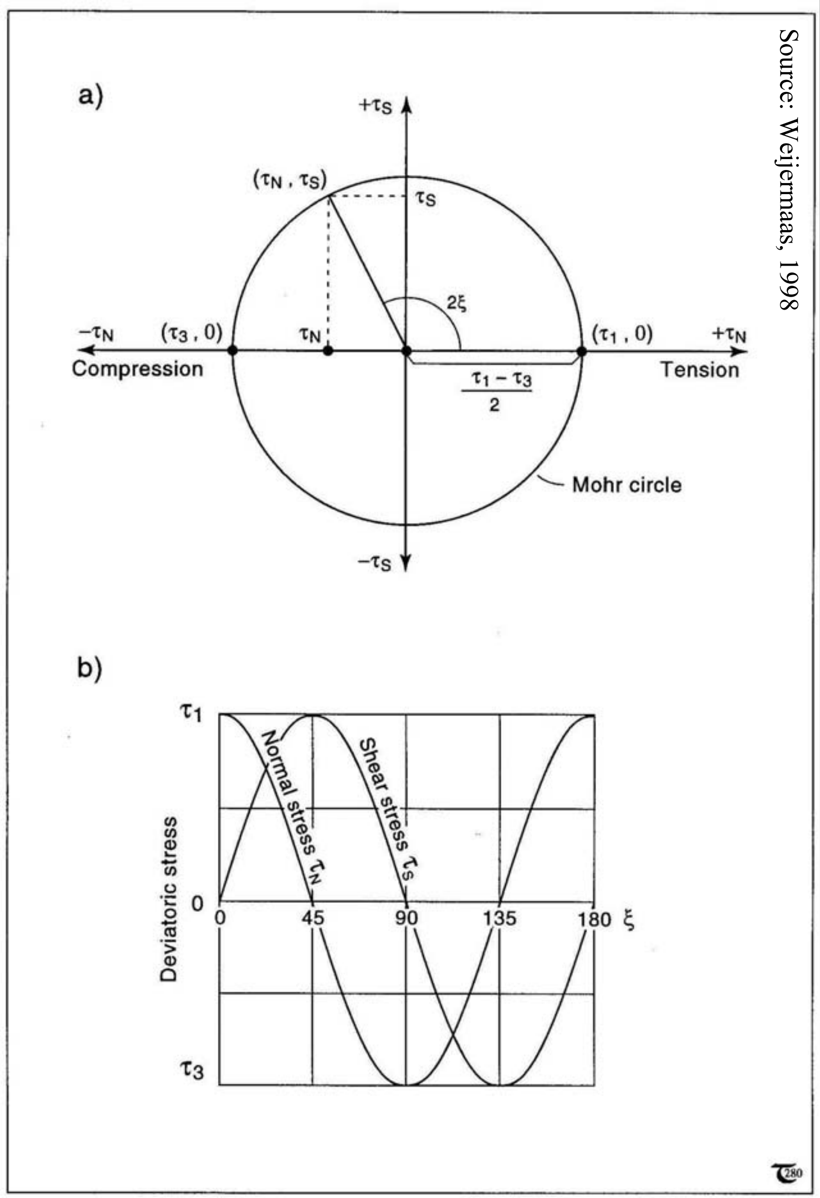
Hydro vs. Shear-Stress Frac

- Hydro Frac: Pressure in borehole exceeds minor horizontal stress in rock; requires proppants to maintain open frac
- Shear Stress Frac: Tangential stress exceeds value required for frictional sliding on existing fracture or fault

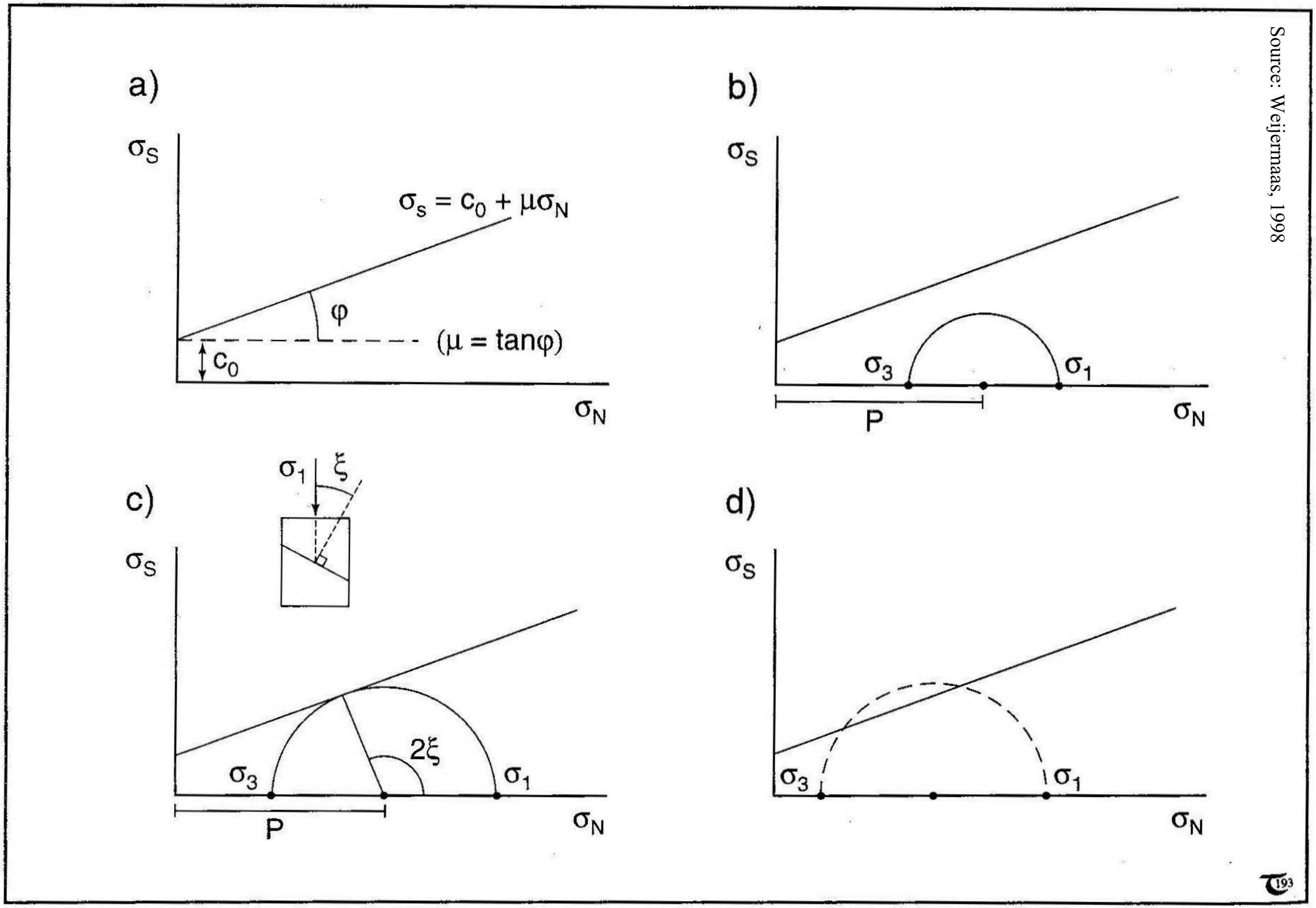


Mohr Circles for Total and Deviatoric Stress





Brittle Failure – Coulomb Criterion



Source: Weijermaas, 1998

Brittle Failure – Coulomb Criterion

Mohr-Coulomb criterion:

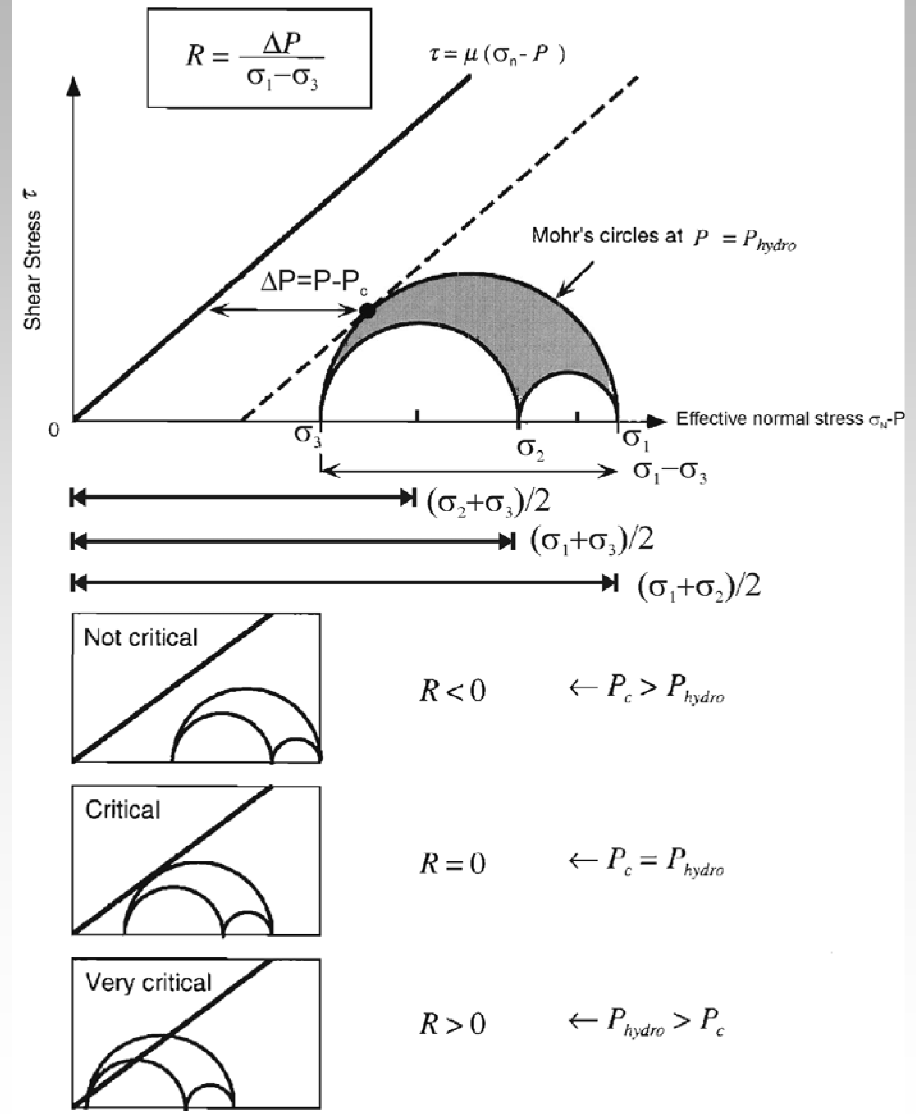
$$\sigma_S = c_0 + \mu \sigma_N$$

$$\xi = \phi/2 - \pi/4$$

Byerlee's Law:

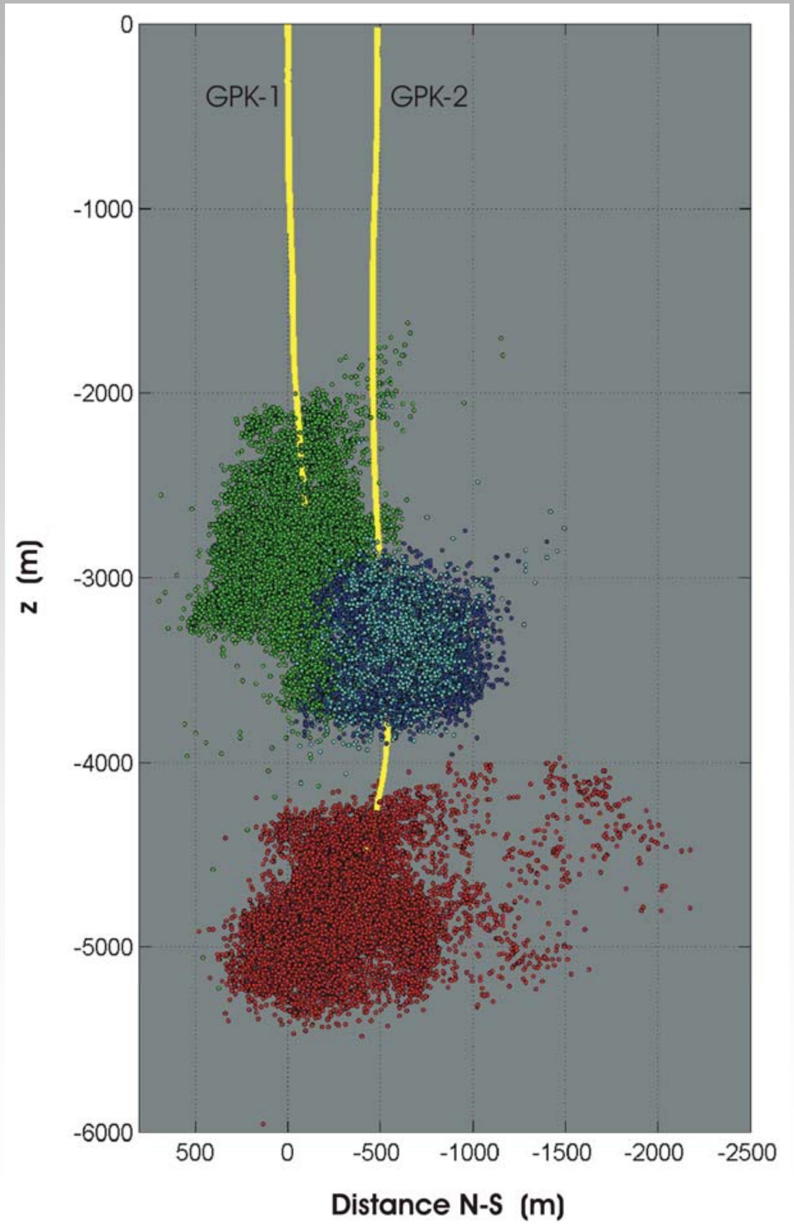
$$\sigma_S = 0.85 \sigma_N$$

($z \leq$ 8 km or $P \leq$ 200 MPa)



Courtesy Dr. Ito Takatoshi

Hot Dry Rock and Enhanced Geothermal Systems



Micro-seismic hypocenters due to four massive hydraulic stimulations in 1993 (green), 1995 (blue), 1996 (cyan), and 2000 (red) in the boreholes GPK-1 and GPK-2 (yellow lines) of the European HDR experimental site at Soultz-sous-Forêts, France

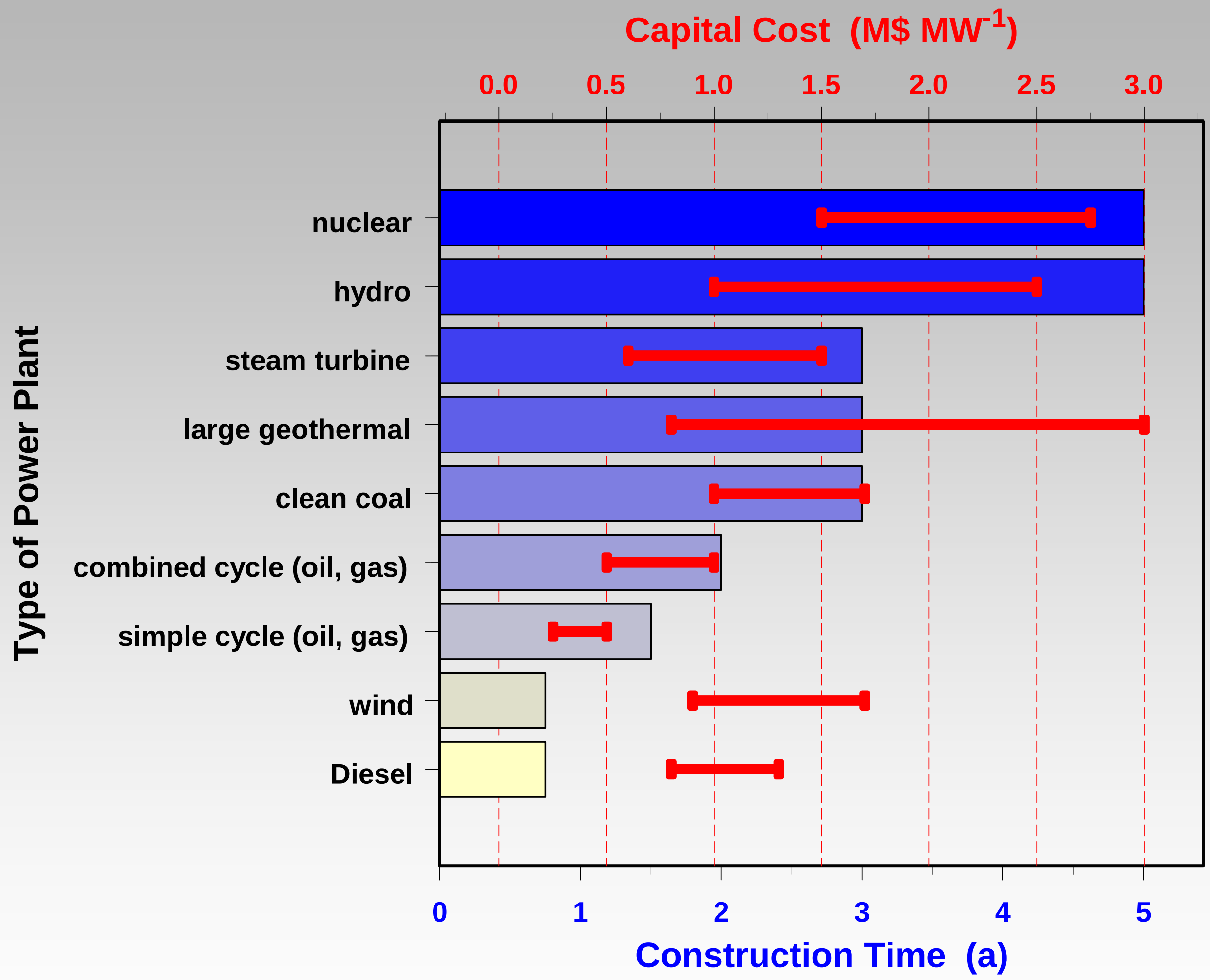
Hot Dry Rock and Enhanced Geothermal Systems

Minimum requirements for a commercially successful HDR installation:

- production **flow rate**: **50 L s^{-1} – 100 L s^{-1}**;
- **flow losses: < 10 %** of injection flow or < 10 L s^{-1};
- **flow resistance** (injection pressure-production pressure)/(production flow rate) **< 100 kPa s L^{-1}**;
- effective **heat exchange surface: > 5 km^2 – 10 km^2**;
- **rock volume** accessed: **> 0.2 km^3**

Systems with these characteristics, developed by **two 5 km deep boreholes about 1 km apart**, aim for a **thermal power of 50 MW$_t$ – 100 MW$_t$** corresponding to an **electric power of 5 MW$_e$ – 10 MW$_e$** delivered over an **operation time of 20 years** at minimum

Cost and construction time



Turnkey investment in US $ (red bars) and average time required for power plant construction (blue bars) based on various kinds of conventional and renewable energy

Turnkey investment (steam fields)

Development of new geothermal dry or wet steam fields and installation of power plants takes **about 3 years**, comparable to construction times for other power stations.

Available numbers for the **specific investment** required for large geothermal steam power plants are **~1 million US $ or € per installed MW** (0.8 M$ MW^{-1} – 3.0 M$ MW^{-1} or 0.6 M€ MW^{-1} – 2.4 M€ MW^{-1}).

Corresponding **production costs of 0.045 € kW^{-1} h^{-1} – 0.091 € kW^{-1} h^{-1}** not too far above the energy price of a clean coal power plant, and competitive compared to other sources of renewable energy, i.e. **comparable to biomass and wind and one or two orders of magnitude below concentrating solar or photovoltaic**, respectively.

Characteristics of 31 steam fields

Average yield (MW_e) per well	Average yield (MW_e) per drilled km	Average number of wells for achieving maximum yield
4.2 ± 2.2	3.4 ± 1.4	9.3 ± 6.1

Turnkey investment (steam fields)

Comparison based on five geothermal power plants built on Iceland 1994−1999: Surface installations contribute about 977 ± 215 $ kW^{-1} to the capital cost; **linear correlation** (R^2=0.97) **between surface cost and installed capacity**:

$$\text{surface cost (M\$)} = -0.9 \pm 4.6 + (1.0 \pm 0.1) \times \text{capacity (MW)}$$

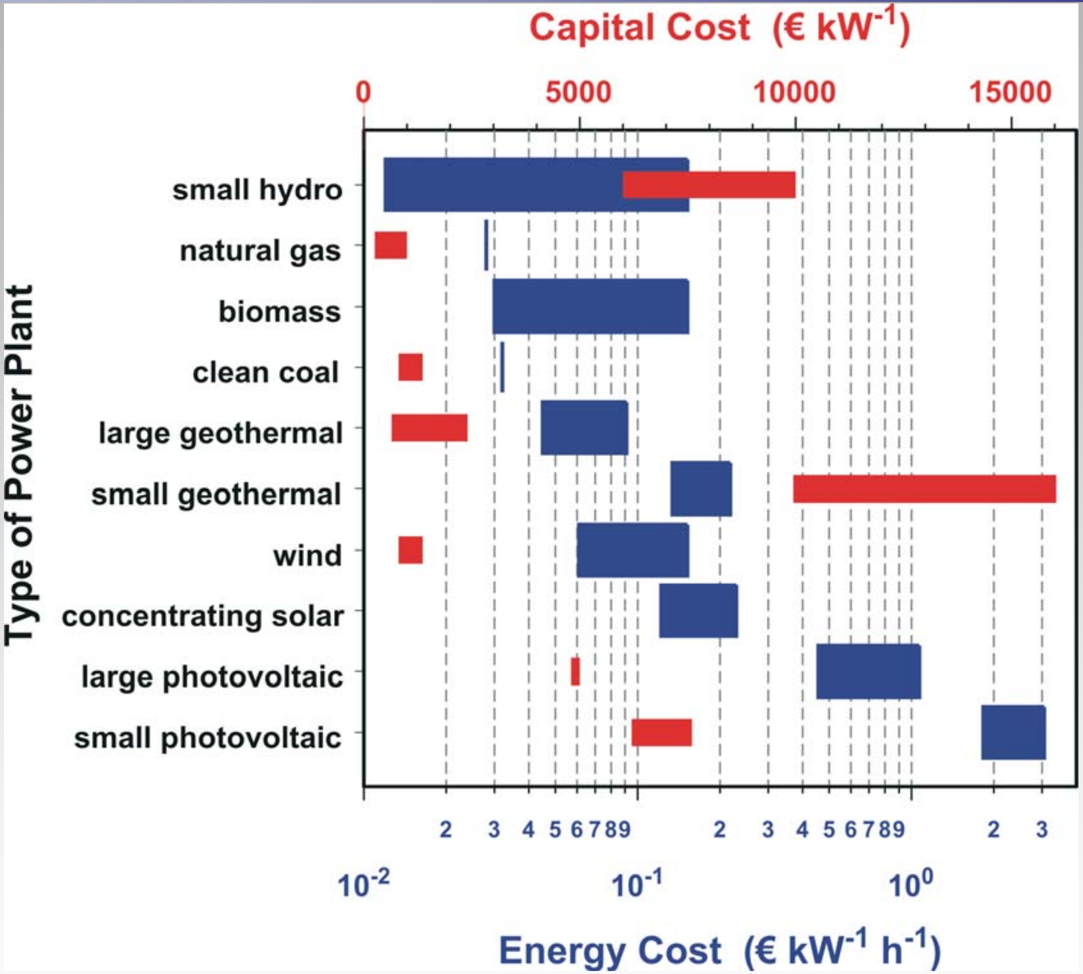
Combined this with results of earlier data survey from 31 geothermal steam fields world-wide yields expression for **total capital cost for a known geothermal field**:

$$\text{cost (M\$)} = -0.9 \pm 4.6 + (1.29 + 0.31/-0.19) \times \text{capacity (MW)}$$

Assuming that exploration in an unknown field requires an additional 50 % of the average number of drill holes, i.e. 4.6 ± 3.0 at a cost of 1.5 M$ each corresponding to an additional cost of 6.9 ± 4.5 M$, this yields an expression for the **total capital cost for an unknown geothermal field**:

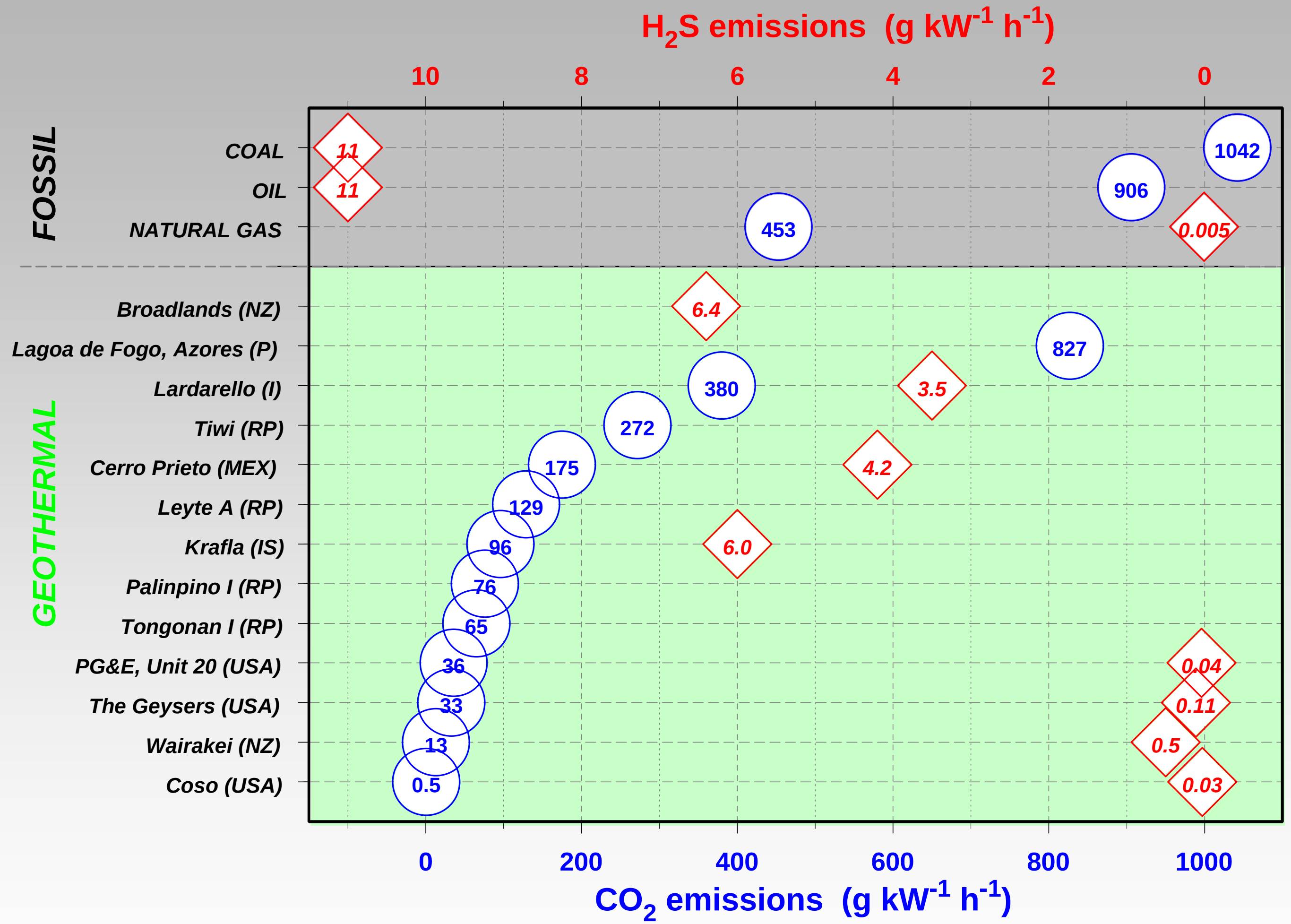
$$\text{cost (M\$)} = 6.0 \pm 9.1 + (1.29 + 0.31/-0.19) \times \text{capacity (MW)}$$

Capital and energy cost



Cost of electricity from various fossil and renewable sources (blue bars) and specific investment cost for various fossil and renewable power plants (red bars). “Large geothermal” and “small geothermal”: steam power plants, and HDR systems with binary power plants, respectively

Pollution

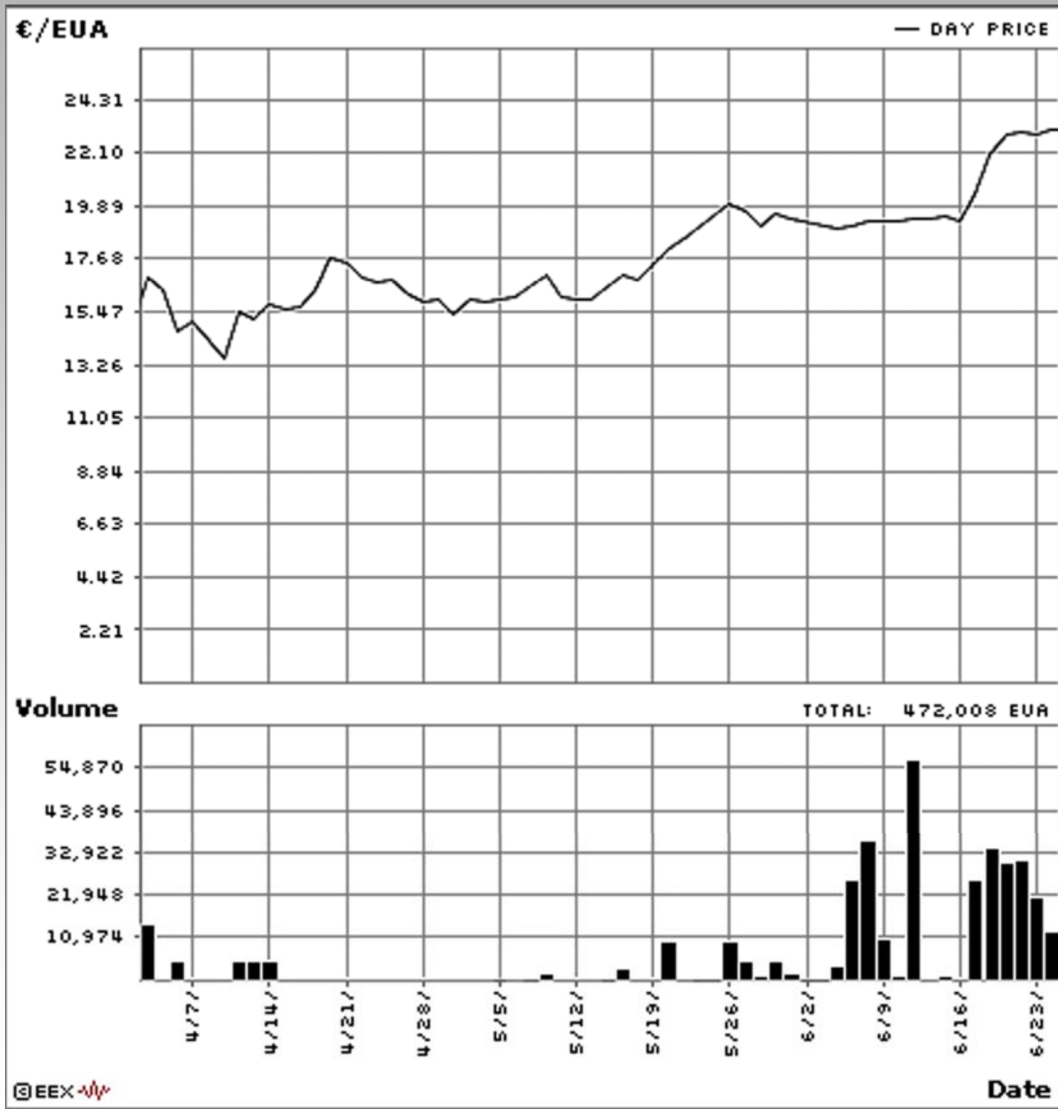


Emission of carbon dioxide and hydrogen sulfide per kW h produced electric energy reported for geothermal power plants in Asia, Europe, North America, and typical fossil power plants (I: Italy, IS: Iceland, MEX: Mexico, NZ: New Zealand, P: Portugal, RP: Philippines

CO_2 - Kyoto protocol

Emission limitations or reduction commitments under the Kyoto protocol			
Country	**Percentage of emissions by the year 2012 relative to the level of 1990 (or the base period)**	**Country**	**Percentage of emissions by the year 2012 relative to the level of 1990 (or the base period)**
Austria	87.0	Liechtenstein	92.0
Belgium	92.5	Lithuania	92.0
Bulgaria	92.0	*Luxembourg*	*72.0*
Canada	94.0	Netherlands	94.0
Czech Republic	92.0	New Zealand	100.0
Denmark	79.0	Norway	101.0
Estonia	92.0	Poland	94.0
Finland	100.0	*Portugal*	*127.0*
France	100.0	Romania	92.0
Germany	*79.0*	Russia	100.0
Greece	*125.0*	Slovakia	92.0
Hungary	94.0	Slovenia	92.0
Iceland	110.0	Spain	115.0
Ireland	113.0	Sweden	104.0
Italy	93.5	Switzerland	92.0
Japan	94.0	Ukraine	100.0
Latvia	92.0		

CO_2 – EU emission allowances



Daily market price from 2 April – 26 June, 2005 for CO_2 emission allowances (EUA) based on the European Carbon Index pub-lished by the European Energy Exchange AG (EEX)§.

Since the official beginning of EUA-trading on 17 December 2004, prices increased from initial 8.45 € per ton of CO_2 to 23 € per ton of CO_2 on 26 June 2005.

§http://www.eex.de

CO_2 – EU emission allowances

<u>Deep borehole heat exchangers</u>:

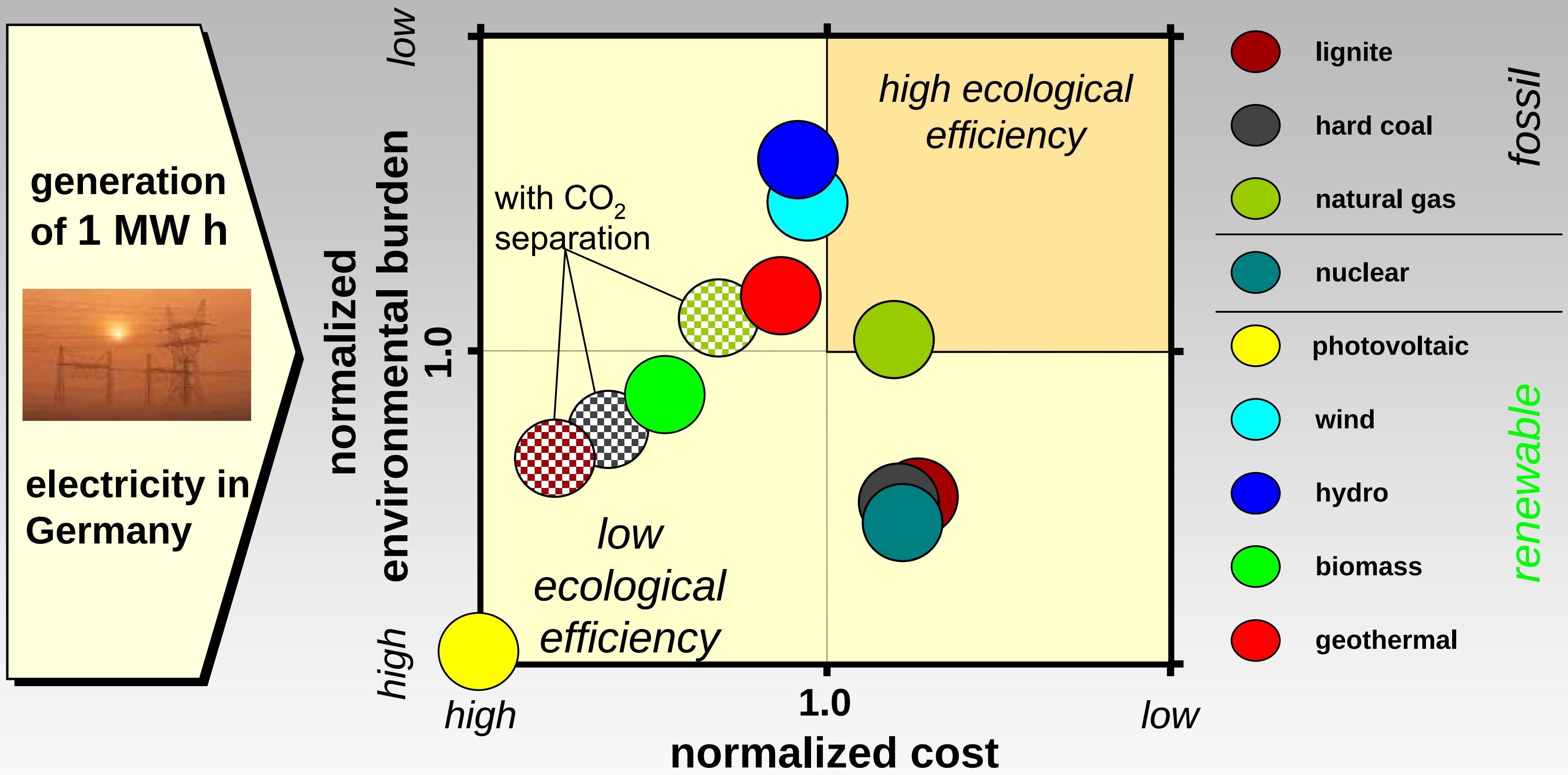
For installed thermal powers of 310 kW_t – 790 kW_t and annual operation times of 6000 h a^{-1} – 8000 h a^{-1} maximum ranges of annual CO_2 reductions are on the order of 250 t – 1260 t if geothermal heat replaces gas, and of 350 t – 1770 t if geo-thermal heat replaces oil in furnaces. Based on an allowance price of 23 € per ton of CO_2 this corresponds to a **financial bonus** of about **5700 € a^{-1}– 29000 € a^{-1}** *if geothermal heat replaces gas*, and about **8000 € a^{-1} – 40100 € a^{-1}** *if geothermal heat replaces oil*.

<u>Steam Power Plants:</u>

CO_2 emissions of fossil power plants are in the range of 0.450 kg kW^{-1} h^{-1} – 1.040 kg kW^{-1} h^{-1}, in contrast to less than 0.200 kg kW^{-1} h^{-1} of CO_2 for most geothermal plants.

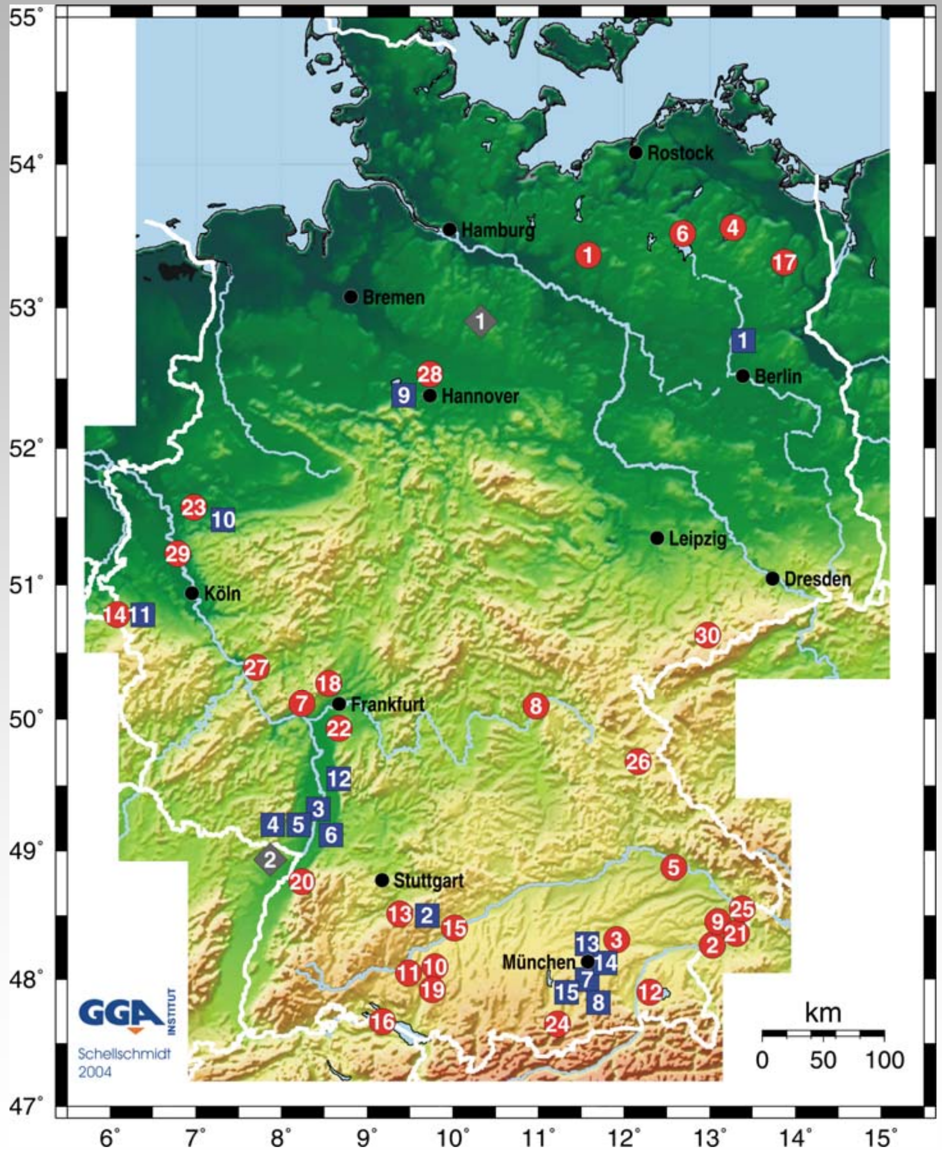
Thus replacing existing oil, gas, or coal fired plants by geothermal plants will result in a reduction on the order of 0.250 kg kW^{-1} h^{-1}, 0.700 kg kW^{-1} h^{-1}, or 0.850 kg kW^{-1} h^{-1}, respectively. Based on an EUA price of 23 € per ton of CO_2 this corresponds to *minimum incentives of* **0.006 € kW^{-1} h^{-1}, 0.016 € kW^{-1} h^{-1}, or 0.02 € kW^{-1} h^{-1}**, *if natural gas, oil, or coal is replaced by geothermal heat*.

Ecological efficiency



Environmental burden vs. cost associated with the generation of electric energy in Germany based on different sources of fossil and renewable primary energy; wind: 5.5 m s^{-1} at 50 m above land surface; biomass: wood)

Status in Germany



Current installations in Germany: red circles: operating; blue squares: planned; grey diamonds: HDR/EGS test sites at Horstberg (1) Soultz-sous-Forêts in France (2) with German contribution

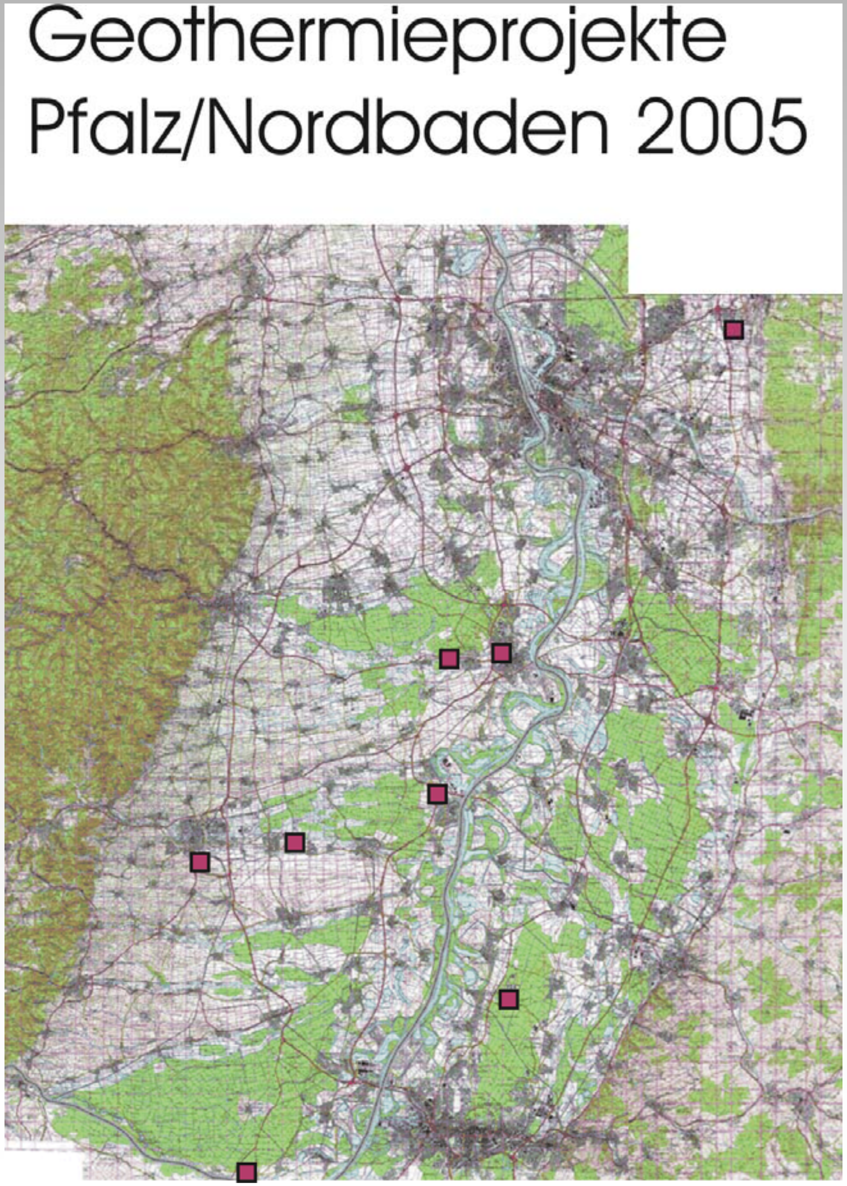
Status in Germany

No.	location	direct use of geothermal energy capacity total MWt	geothermal MWt	annual use GWh/a	use	temperature °C	maximum flow rate l/s	miscellaneous
1	Neustadt-Glewe	10,70	6,50	17,95	P, D	97	35,0	doublet, ORC plant
2	Simbach-Braunau	40,00	7,00	67,00	D, S	80	73,9	doublet
3	Erding	18,00	8,00	28,00	D, S, W	65	24,0	direct heat exchanger and heat pump in parallel; cooled thermal water supplied as drinking water (40% of municipal demand
4	Neubrandenburg	10,00	5,80	26,60	D	54	42,0	2 doublets, heat pump
5	Straubing	5,40	4,10	11,83	D, S, W	36	40,0	doublet, production of potable water
6	Waren (Müritz)	5,20	1,50	11,20	D	60	17,0	doublet, no heat pump
7	Wiesbaden	1,76	1,76	4,54	H, S	69	13,0	springs
8	Staffelstein	1,70	0,30	3,72	H, S	54	4,0	
9	Birnbach	1,40	1,40	3,07	H, S	70	16,0	doublet, 2 heat pumps
10	Biberach	1,17	1,17	0,80	H, G	49	40,0	
11	Bad Buchau	1,13	1,13	2,47	H, S	48	30,0	
12	Bad Endorf	1,00	1,00	2,19	H, S	60-65	4,0	singlet, use of high caloric in water solued natural rock gas is planed
13	Bad Urach	1,00	1,00	1,50	H, S	58	10,0	
14	Aachen	0,82	0,82	3,38	H, S	68		
15	Neu-Ulm	0,70	0,70	1,53	S	45-50	2,5	singlet
16	Konstanz	0,62	0,62	2,00	S	29	9,0	
17	Prenzlau	0,50	0,50	1,10	D	108		deep VHE of 2800 m depth
18	Frankfurt-Höchst	0,45	0,45	0,99	H			32 VHEs of 50 m depth each
19	Bad Waldsee	0,44	0,44	0,96	H, S	30	7,0	
20	Baden-Baden	0,44	0,44	1,43	H, S	70	3,0	
21	Bad Füssing	0,41	0,41	0,90	H, S	56	60,0	
22	Langen	0,33	0,33	0,72	H			154 VHEs of 70 m depth each provide heating and cooling the German Air Traffi Control (DFS) Headquarter Langen
23	Gladbeck	0,28	0,28	0,61	H			32 VHEs of 60 m depth each and 1 HHC provide heating and cooling to an office complex
24	Kochel am See	0,21	0,21	0,46	H			21 VHEs of 98 m depth each provide space heating to 35 apartments
25	Griesbach	0,20	0,20	0,44	H, S, G	60	5,0	
26	Weiden	0,20	0,20	0,44	H, S	26	2,0	
27	Bad Ems	0,16	0,16	0,72	H, S	43	1,0	
28	Hannover	0,15	0,15	0,08	H			122 piles of 20 m depth each with a total pipe lenth of 37 km provide space heating and cooling to a bank office complex
29	Düsseldorf	0,12	0,12	0,26	H			73 VHEs of 35 m depth each provide spac heating and cooling to an office complex
30	Ehrenfriedersdor	0,12	0,12	0,26	H	7 - 9	6	thermal use of mine water (depth: 100-250 m)

No.	location	direct use of geothermal energy capacity MWt	power generation capacity MWe	use	T °C	maximal flow rate l/s	miscellaneous
1	Groß Schönebeck			P	150	21	HDR-system
2	Bad Urach		1,00	P	175		HDR-system
3	Speyer	24,00	5,40	P, D	140	25	3 injection and 6 production boreholes
4	Landau in der Pfalz	7,00	2,50	P, D	150	50 - 70	doublet
5	Offenbach an der Queich		3,50	P	150	100	aquifer system with ORC-plant 2 production and 1 injection borehole
6	Bruchsal			P	120		doublet, ORC-plant
7	Isar-Süd (München)	30,00	2,00	P, D			doublet, KALINA cycle,
8	Unterhaching	16,00	3,70	P, D	107	100	doublet, KALINA cycle, max capacity 41 MW(th)
9	Hannover (GeneSys)	4,00		H	135	14	singlet, use of fault zones
10	Bochum (Prometheus)	10,00		H	115		HDR-technology
11	Aachen (SuperC)	0,48		H	85		deep vertical heat exchanger
12	Weinheim (Miramar)	2,30		S	65		doublet
13	Unterschleißheim	20,60		D, S	79	90	doublet
14	München-Riem	12,00		D	90	50	doublet
15	Pullach i. Isartal			D			

Geothermal installations operating (left) and planned (right) in Germany (Schellschmidt et al., 2005)

Status in Germany



Current HDR/EGS-projects for geothermal power production in the Rhine graben