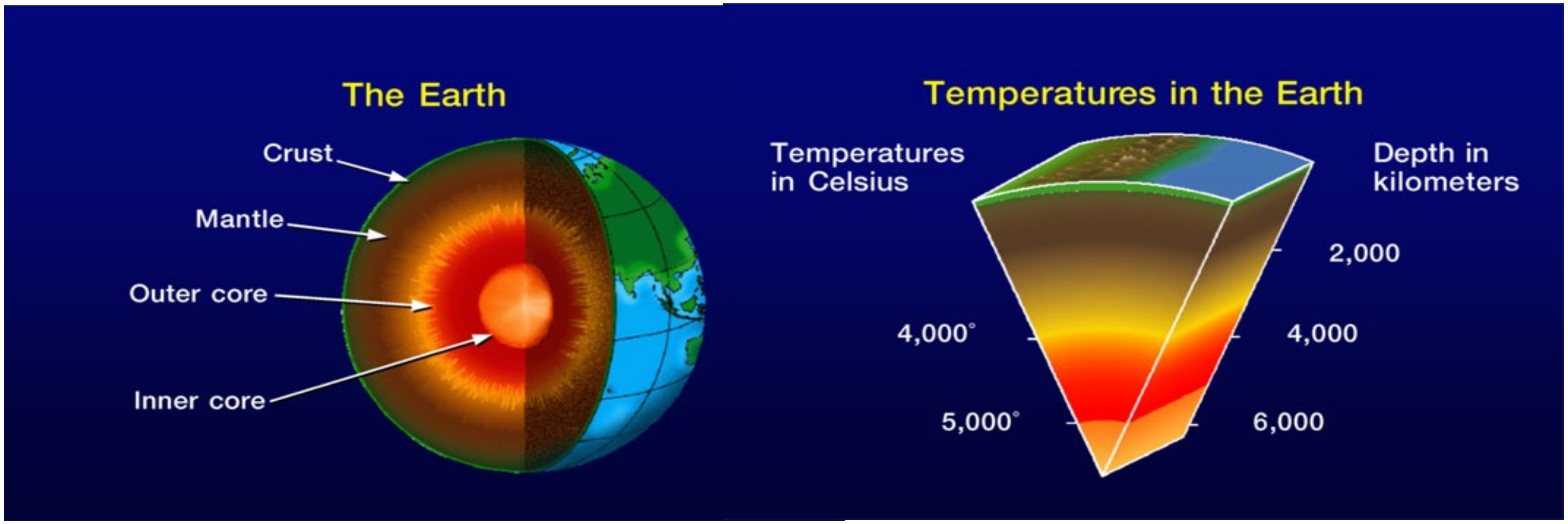
Geothermal energy

Learning outcomes

- Geothermal energy:
  - Know the intrinsic geothermal heat flux and average geothermal heat gradient
  - Explain the (renewable) character of geothermal heat
  - Know different geothermal systems (for power generation) (dry vs. hydro-reservoirs; dry steam – flash process – binary cycle)
  - Explain and calculate 1st law (energy) and 2nd law (exergy) efficiency for geothermal systems
  - Know different geothermal systems for heat applications

Earth's subsurface temperatures



Zone	Distance from surface [km]	Temperature [°C]	Density [kg/dm^3]
Ground	0	ambient	2.7
Crust (bottom)	35	1100	3.3
Mantle (bottom)	2900	3700 to 4500	5.7 to 10.2
Liquid (iron) core	5100	4300 to 6000	11.5
Solid inner (iron) core	6350	4500 to 6600	11.5

average gradient 30 K/km

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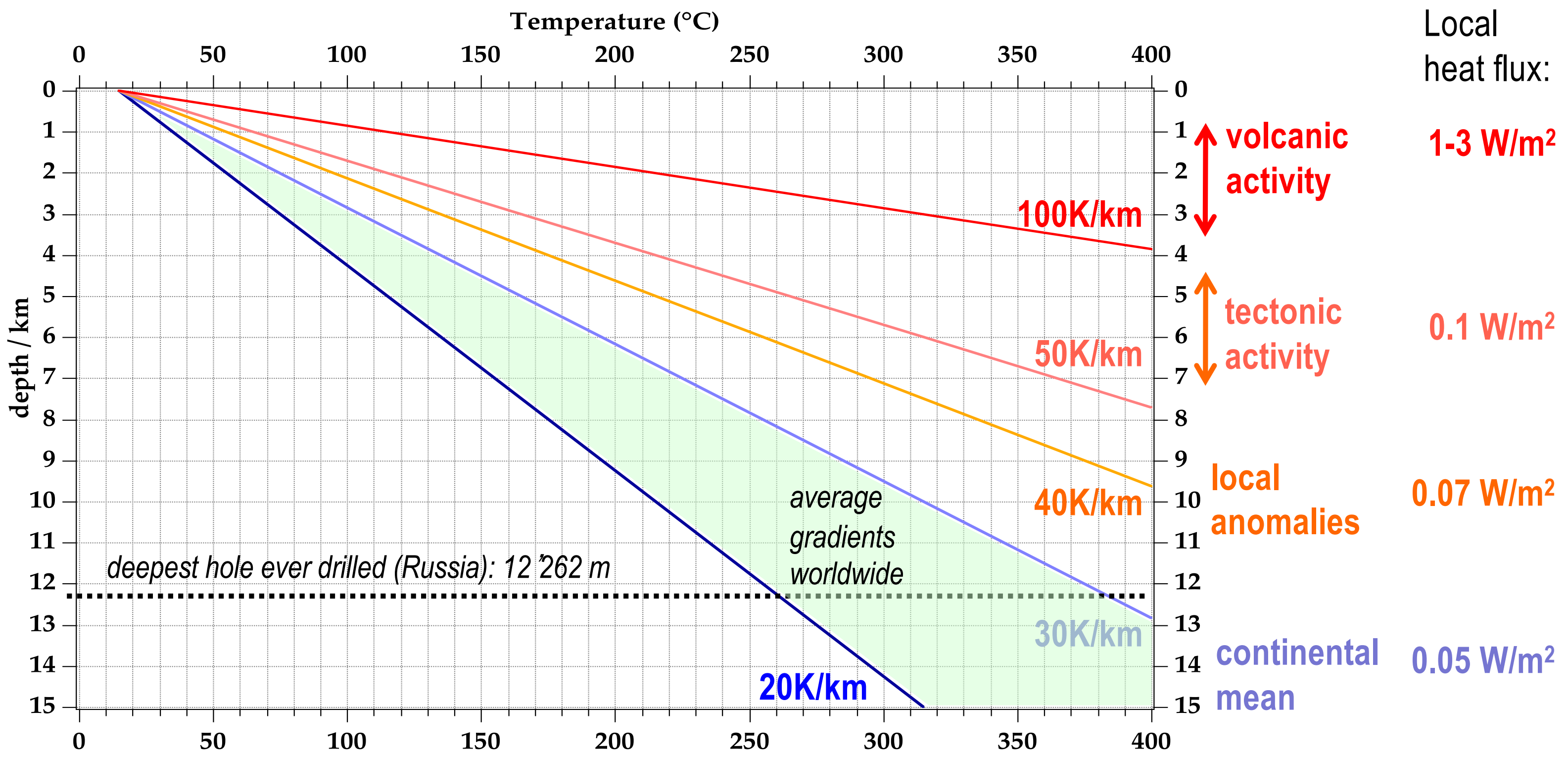
Temperature gradient in the Earth's crust (K/km)



➔ ***the <u>sustainable</u> intrinsic geothermal heat flux is very low !***

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Geothermal potential (world)

- The average geothermal heat flux is approximately **50 – 60 mW/m^2**, resulting from:
  - the flux from the hot Earth interior (= residual heat from the Earth's origin; tidal friction)
  - within the crust (0 to 50 km): radioactive decay (^{40}K, U, Th)

- Worldwide: 50 mW/m^2 → multiplied with area of the 5 continents (135 Mkm^2) => 6.75 TW_{heat}
  - assuming 20% electrical efficiency and 8000 h load:

  => 1.35 TW_{el} and 11'000 TWh_{el} (= 40% of current world electrical production)

  but exploiting *every square meter* of land on the planet!

- Geothermal power can only deliver a small contribution worldwide (on the order of ≈1 %), and it has to come from local anomalies

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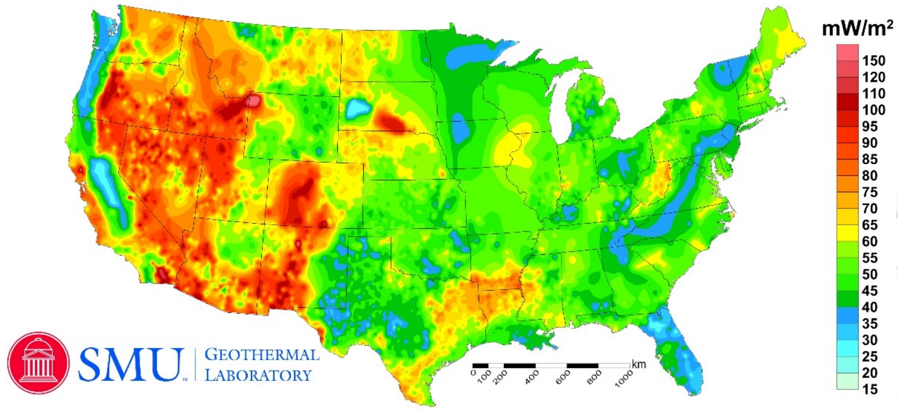
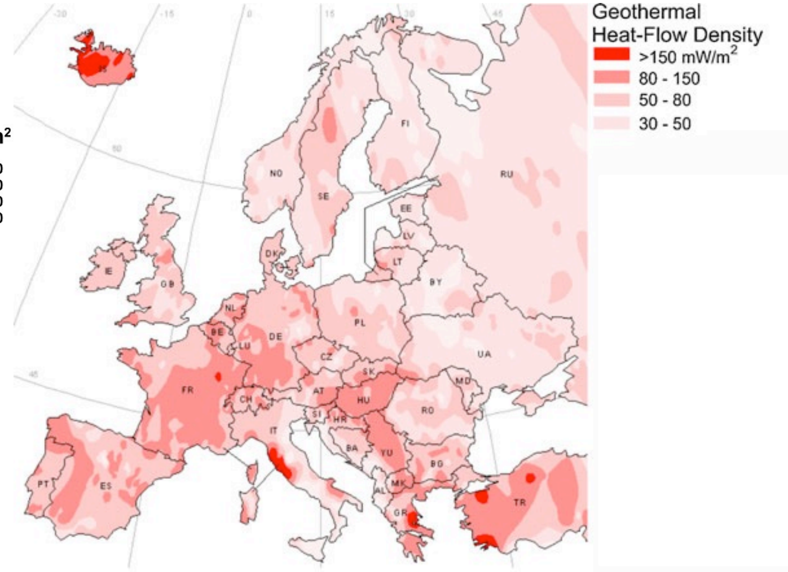
Geothermal heat flux

- USA / Europe

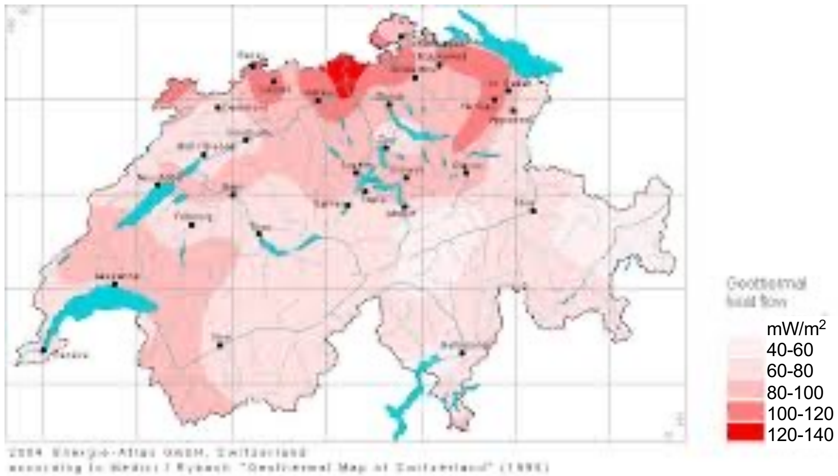
SMU Geothermal Laboratory Heat Flow Map of the Conterminous United States, 2011



Reference: Blackwell, D.D., Richards, M.C., Frone, Z.S., Batir, J.F., Williams, M.A., Ruzo, A.A., and Dingwall, R.K., 2011, "SMU Geothermal Laboratory Heat Flow Map of the Conterminous United States, 2011". Supported by Google.org. Available at http://www.smu.edu/geothermal.



- Switzerland



Geothermal potential (Switzerland)

- For Switzerland: 65 mW/m^2 → with area 41'000 km^2 => 2.67 GW_{heat} or 84 PJ/yr.
  Assuming 20% electrical efficiency and 8000 h/yr load, max. deliver 4 TWh_{el} from 500 MW_{el}
  (again when collecting this heat flux *from every square meter*!)

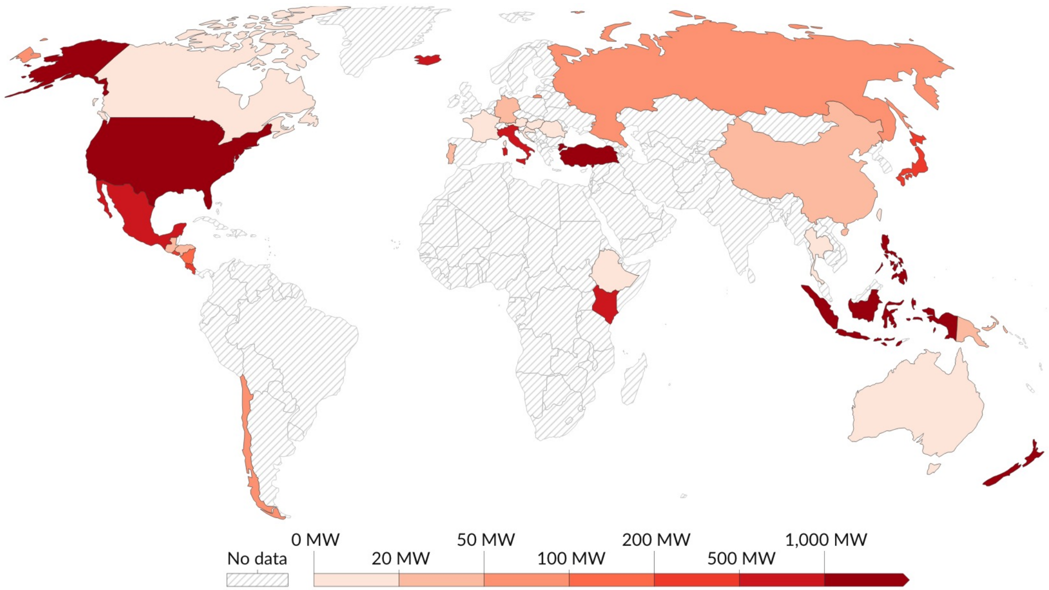
- This compares to the yearly Swiss electrical need of 60 TWh_{el} from ~25 GW_{el} installed power, or to the yearly present heating needs of ~400 PJ

- Taking Swiss population density of 200 people / km^2, which is 5000 m^2 per person, it follows that 65 mW/m^2 * 5000 m^2 = 325 W_{heat} / person → 65 W_{el} / person (20%)
  (compare to total electrical end-consumption = 850 W_{el} per person and 1300 $W_{thermal}$ end-use per person for space heating + hot water)

- The intrinsic geothermal heat flux is too low
- We can extract much more heat from the underground, but then we are not operating in a sustainable fashion

Geothermal reality for power production

- 15 GW_{el} supplied worldwide
- Iceland gets 30% of its electricity from geothermal, but has only 300'000 inhabitants !
- USA is number 1 and has 2.587 GW_{el} installed geo-power, which produces 16 TWh_{el}, but this is only 0.3% of the USA electricity
- Volcanically active countries around the Pacific 'Ring of Fire' can provide a significant share of their needs from geo-energy



Country	Power [GW]	% of elec.
USA	2.587	0.3
Philippines	1.928	27
Indonesia	2.131	3.7
Turkey	1.613	0.3
Mexico	0.906	3
Italy	0.797	1.5
NZ	0.984	14.5
Iceland	0.756	30
Japan	0.525	0.1
El Salvador	0.204	14
Kenya	0.824	38
Costa Rica	0.262	14
Nicaragua	0.153	9.9
World	**15**	**0.4**

> 85 TWh_e

https://ourworldindata.org/grapher/installed-geothermal-capacity?time=latest

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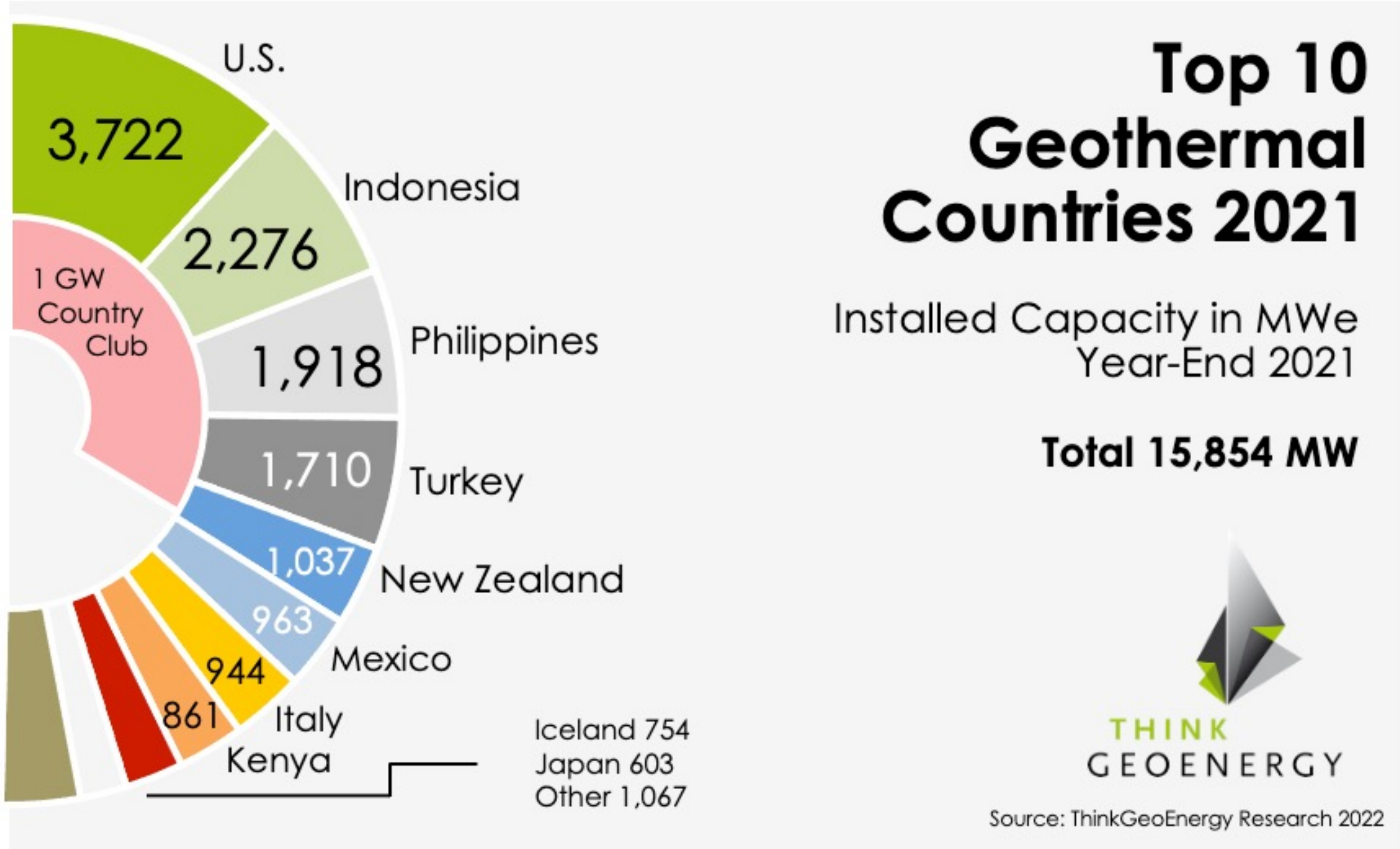
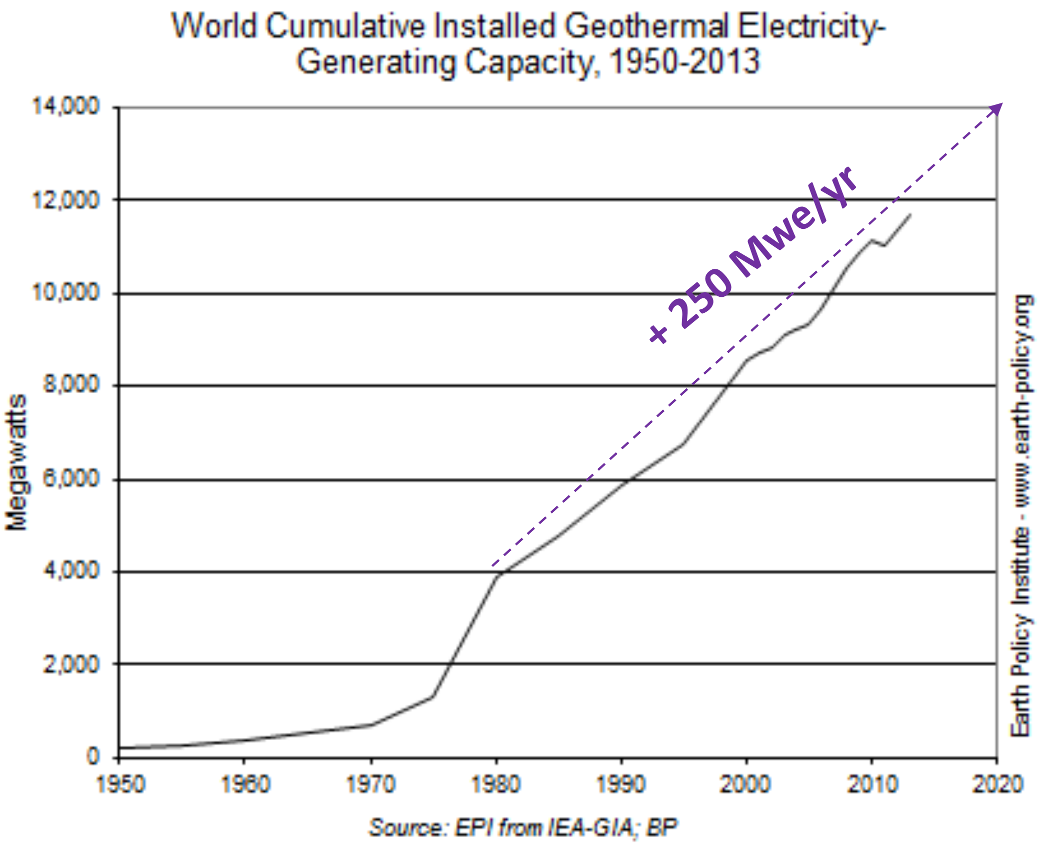
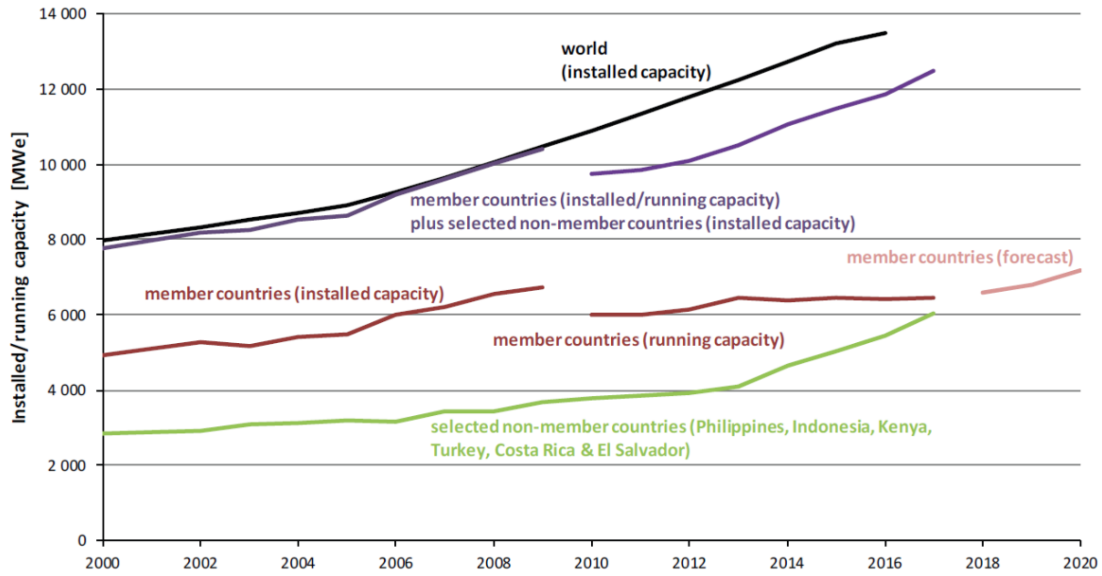
Power production



16 GWe
assuming 8000h
$\Rightarrow$ 128 TWhe
= 0.5% of world electricity

Geothermal reality for power production





Geothermal power statistics, IEA Geothermal, 2017

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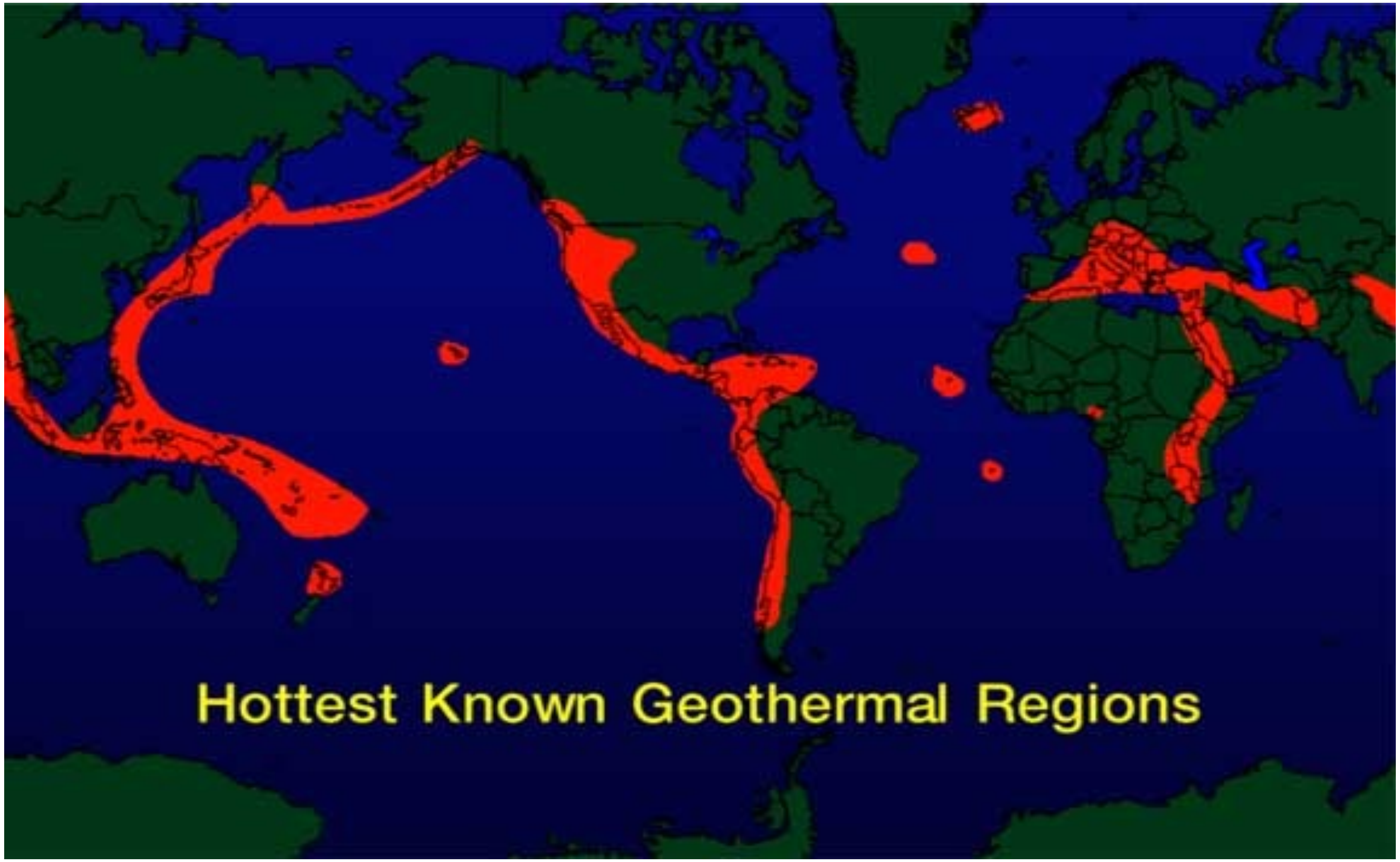
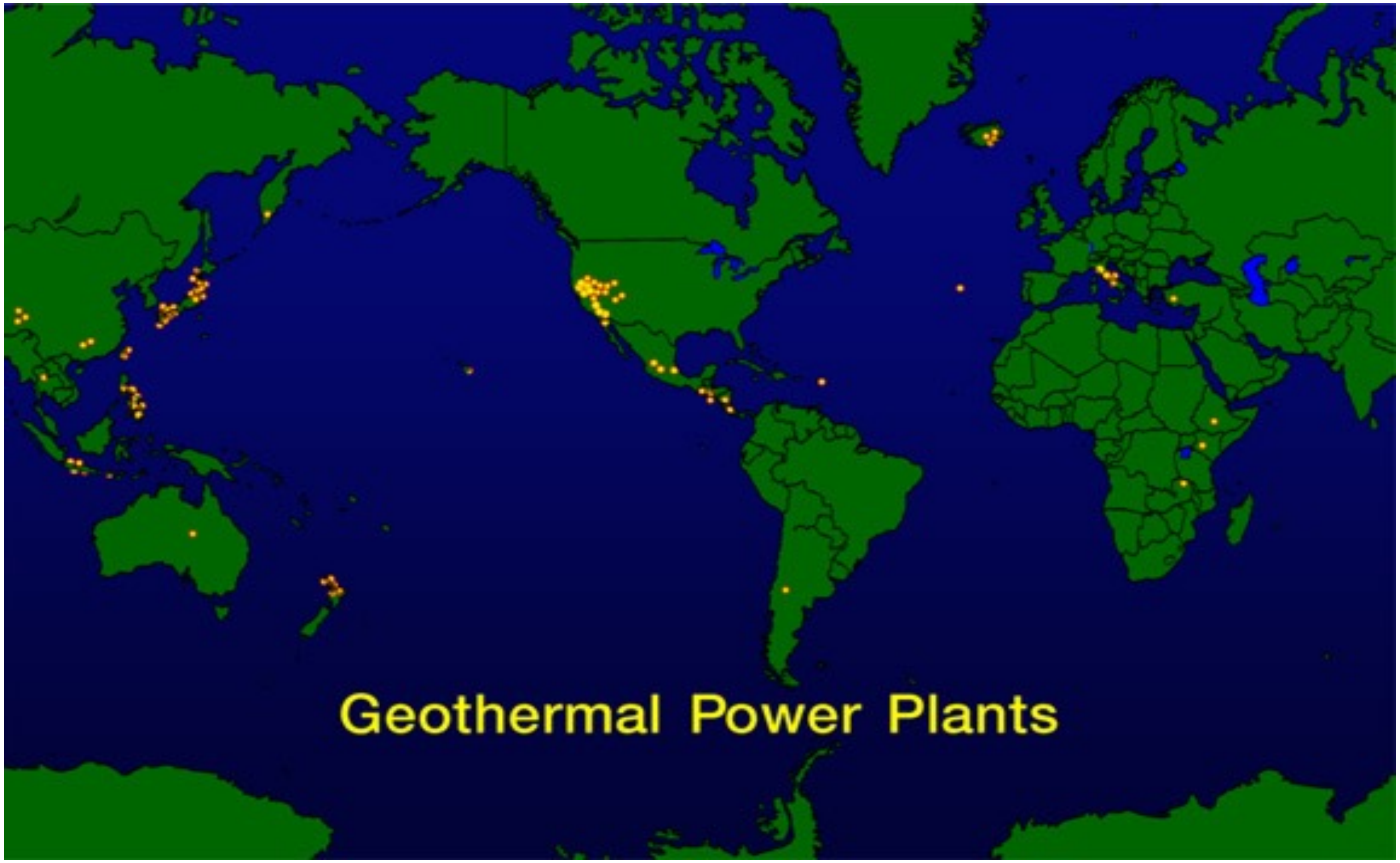
Occurrence – Locations – 'Ring of Fire'



Distribution of geothermal plants



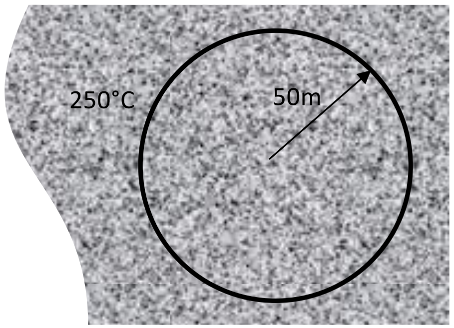
Italy (Tuscany) as pioneer

1st plant worldwide, 1911, in Larderello

- 200°C at 1 km depth; max 437°C at 3.2 km
- 1 W/m² heat flux; ca. 200 km² active area
- 160-250°C, superheated steam 4-20 bar
- average flux 25 t/h (7 kg/s), max 350 t/h
- **800 MW_{el}, 6 TWh_{el}; 2% of Italy's power**

Some general features of geothermal power

- Example:



Extract power for 10 MW plant: we allow soil cooling from 250°C to 200°C, and heat H_2O from 40 to 200°C

For heat transfer fluid water: $P = 10MW = \dot{V} \overbrace{\rho}^{1000kg/m^3} \overbrace{c_p}^{4186J/kgK} \overbrace{\Delta T}^{200-40°C} \rightarrow \dot{V}(H_2O) = 15\ l/s$

Heat available in ground (assume rock, 50 m radius, 1 km deep, cooled to 200°C):

$$Q_{avail} = V\ (soil)\ \underbrace{\rho}_{\frac{2500kg}{m^3}}\ \underbrace{c_p}_{\frac{1000J}{kgK}}\ \underbrace{\Delta T}_{50K} = \ 10^{15}\ J$$

Rock is cooled to 200°C in: $t = \frac{Q}{P} = 3{,}1\ years$

Recharge by conduction:

Heat flow: $\dot{Q} = A \frac{\Delta T}{\Delta x} k = 2\pi(50m)x1km * \frac{1K}{m} * 1 \frac{W}{mK} = 314\ kW \Rightarrow \frac{Q_{avail}}{\Delta t} \rightarrow \Delta t = 100\ years$

- **Can be unsustainable** !
  - if heat extraction rate > geothermal heat flux => the soil is cooled down (v. slowly)
  - power production must last min. 25 years (and can last up to centuries) so as to justify the investment
- Time lapse from discovery to production can be long too
  - e.g. Miravalles (Costa Rica) discovered in 1976 but first power generated in 1994
- **Baseload power** (renewable; independent from season or climate)
- Geothermal water/steam = **'free fuel'**
- Borehole drilling is very **expensive**
  - the technology exists from hydrocarbon reservoirs exploration (oil, gas), which can afford a few failed drillings, as the reward from fossil fuel (unlike geothermal heat) is very high!

Classification of geothermal systems

They are related to young **igneous rock*** intrusions in the upper earth crust

- Magma
- **Hot dry rock (HDR)**
- Convective **hydrothermal** reservoirs ('**wet**')
  - *vapor* dominated
  - *liquid* dominated

} *exploitation in geothermal power plants*

* Igneous rock is one of the 3 main rock types, formed through the cooling and solidification of magma or lava. (The other 2 are sedimentary and metamorphic rock.)

HDR ------------------------> **Hydrothermal reservoirs**

increasing water permeability

dry **wet**

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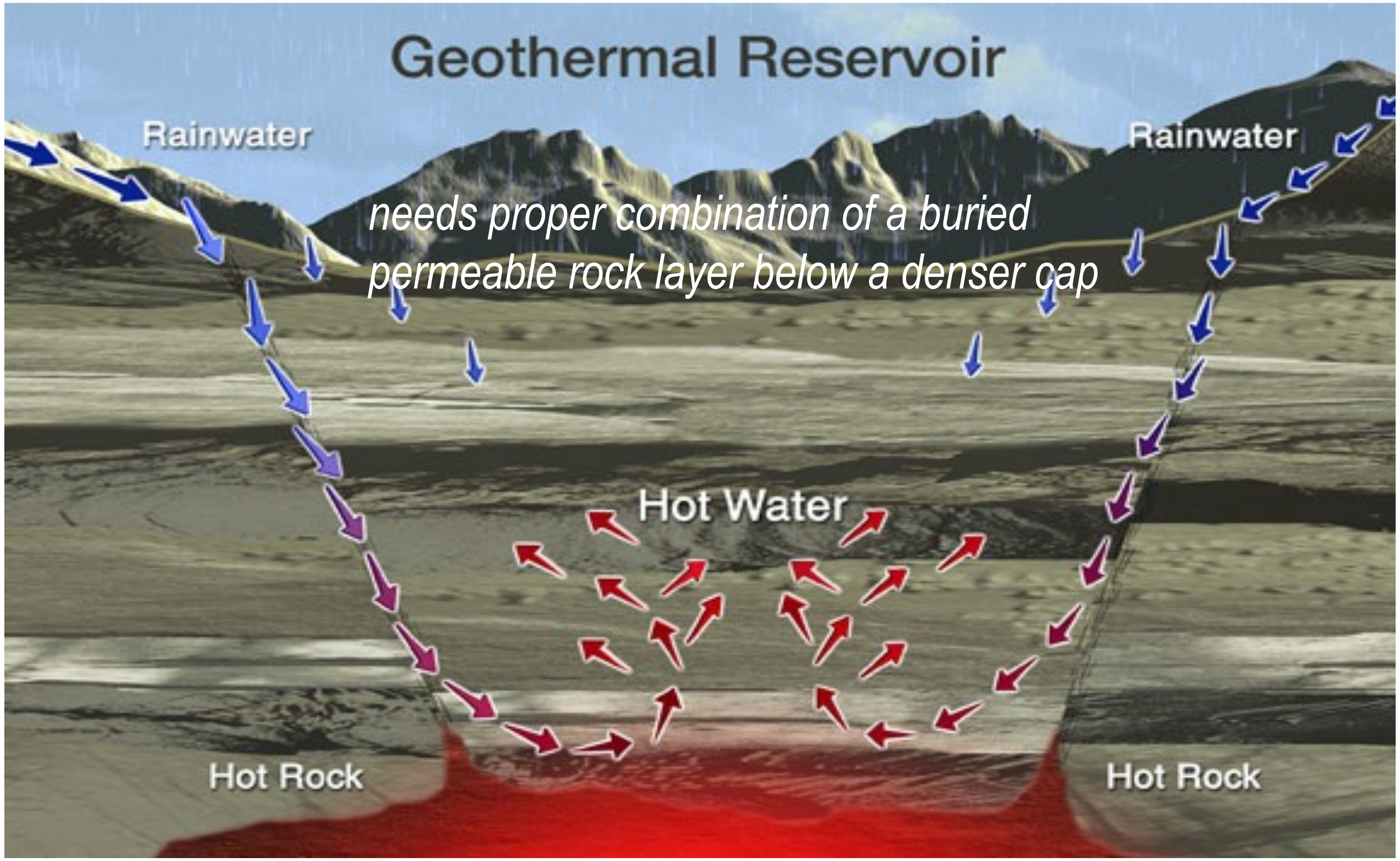
Hydrothermal reservoirs



Classification of hydrothermal reservoirs

Characteristic	Temperature	Depth - Location	Plant type
low-T water	100° C – 150° C	< 3 km gradient 50 K / km selected sites	**Binary**, ORC
high-T water	150° C – 370° C	< 2 km gradient >100 K / km anomalous sites	**Flash**
vapor	>200° C	< 2 km Larderello, …	**Dry** steam

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Different forms of geo-energy exploitation

1. Earth heat probe
2. Groundwater use
3. Geo-structures
4. Earth heat probe, field
5. Deep earth heat probe
6. Thermal bath

Hydrothermal, intermed. depth:

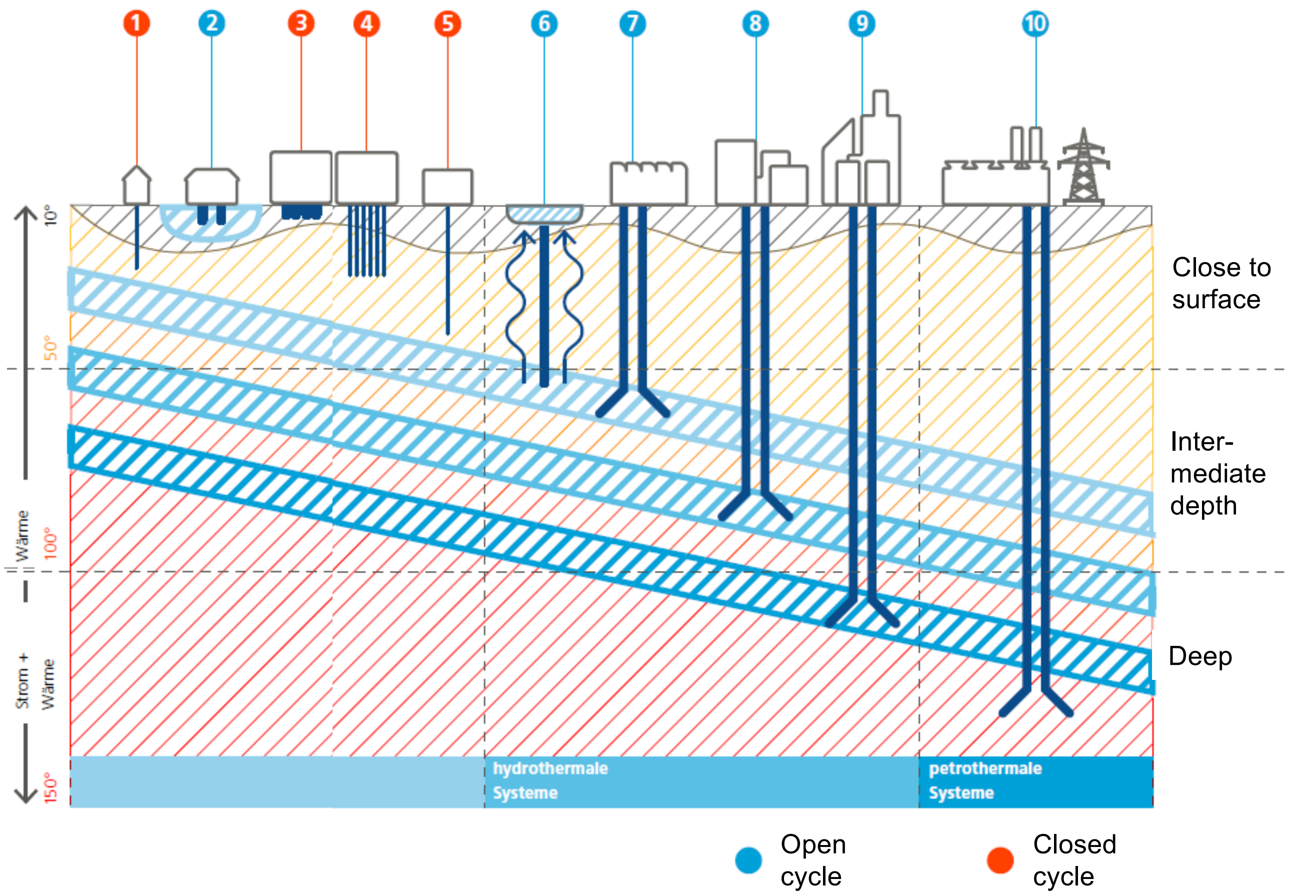
7. Heat for industry, agriculture
8. Heat for heating and hot water

Hydrothermal, deep:

9. Heat and power

Petrothermal:

10. Heat and power



Energie Schweiz: Geothermie in der Schweiz, 2006

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Temperature level usage

Enhanced Geothermal Systems

Electricity generation
Heat (industry, buildings)
Cogeneration

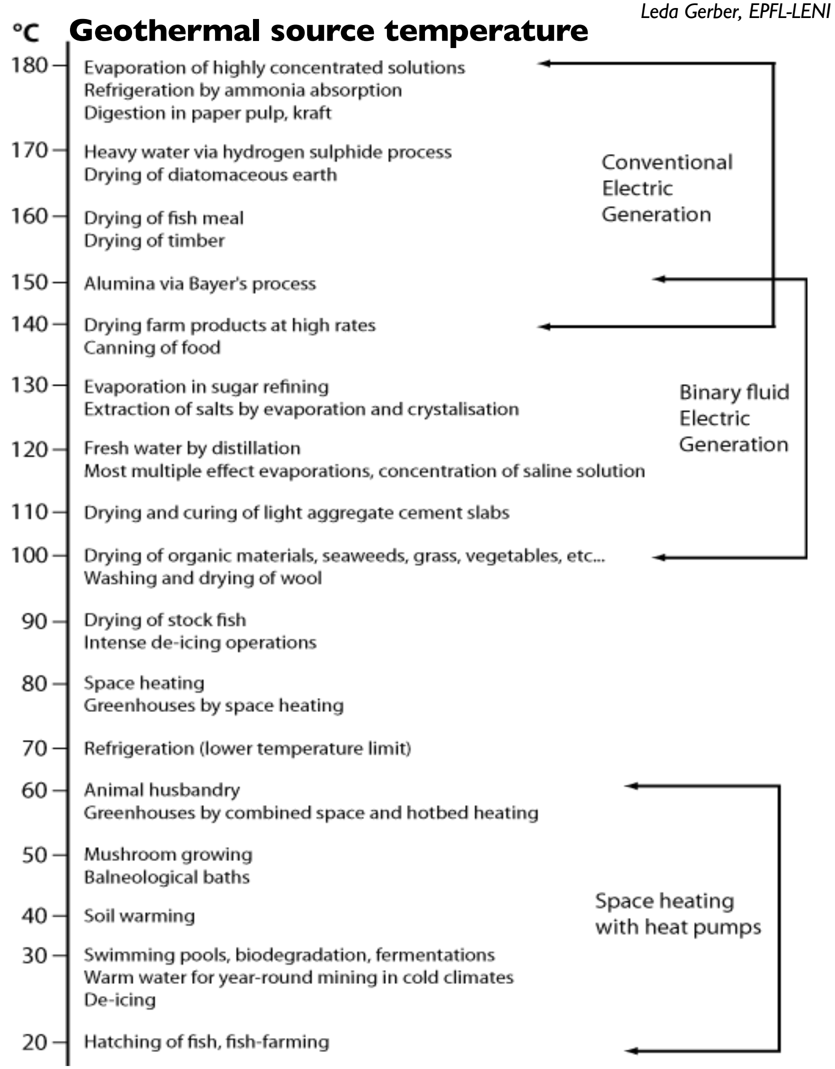
EGS :
3’000 -10’000 m*
90 - 350 ° C

http://www.youtube.com/watch?v=vhSGKIrlVuw

Direct heat use

Heat pumps for building heating

Leda Gerber, EPFL-LENI



•J. Tester et al, *The Future of Geothermal Energy – Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st century*, MIT technical report, 2006

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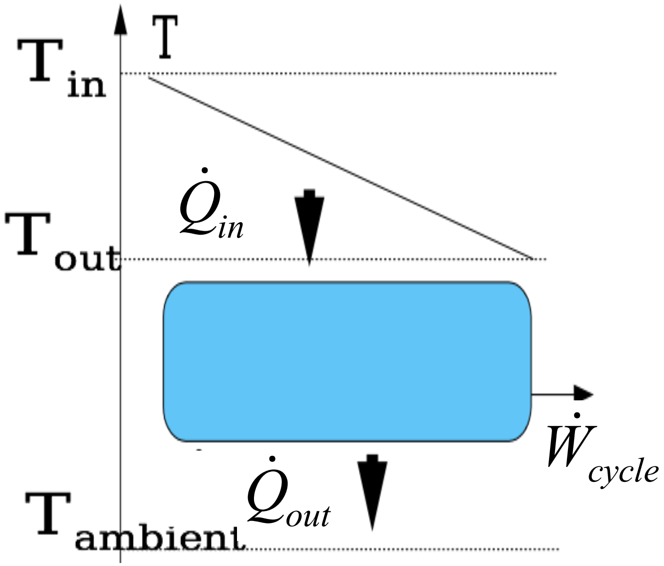
Electricity production potential

Thermodynamics :

- Hot source (geothermal resource)
- Cold source (river or ambient air)



Maximum available power (exergy):

$$\dot{Ex} = \left(1 - \frac{T_0}{T_h}\right)\dot{Q}_{in}$$

Carnot factor

$$\eta = \frac{\dot{W}_{cycle}}{\dot{Q}_{in}}$$

Electrical efficiency – ***Energy***

no account for T levels (energy quantity)

$$\varepsilon = \frac{\dot{W}_{cycle}}{\left(1 - \frac{T_0}{T_h}\right)\dot{Q}_{in}}$$

Exergy efficiency - ***Exergy***

accounts for T levels

(energy quality)

Determination of the hot source average temperature

- Logarithmic mean temperature difference of heat exchange (HEX)

- Heat exchange between a hot fluid, cooling from $T_{h,in(1)}$ to $T_{h,out(2)}$, and a cold fluid, warming from $T_{c,in(1)}$ to $T_{c,out(2)}$, learns us that

$$LMTD = \frac{(T_{h,1} - T_{c,1}) - (T_{h,2} - T_{c,2})}{\ln\left[\frac{T_{h,1} - T_{c,1}}{T_{h,2} - T_{c,2}}\right]}$$

and the transferred heat: $Q = U.A.LMTD$

with U = heat transfer coefficient ($W/m^2 \cdot K$) and A = HEX area (m^2)

- The geothermal reservoir is ***not a constant*** temperature hot source;

  heat is extracted at $T_{h,in}$ and reinjected at $T_{h,out}$;

  the *average hot source temperature T_h*

  is then determined from its logarithmic mean :

$$LMT = \frac{(T_{h,in} - T_{h,out})}{\ln\left[\frac{T_{h,in}}{T_{h,out}}\right]}$$

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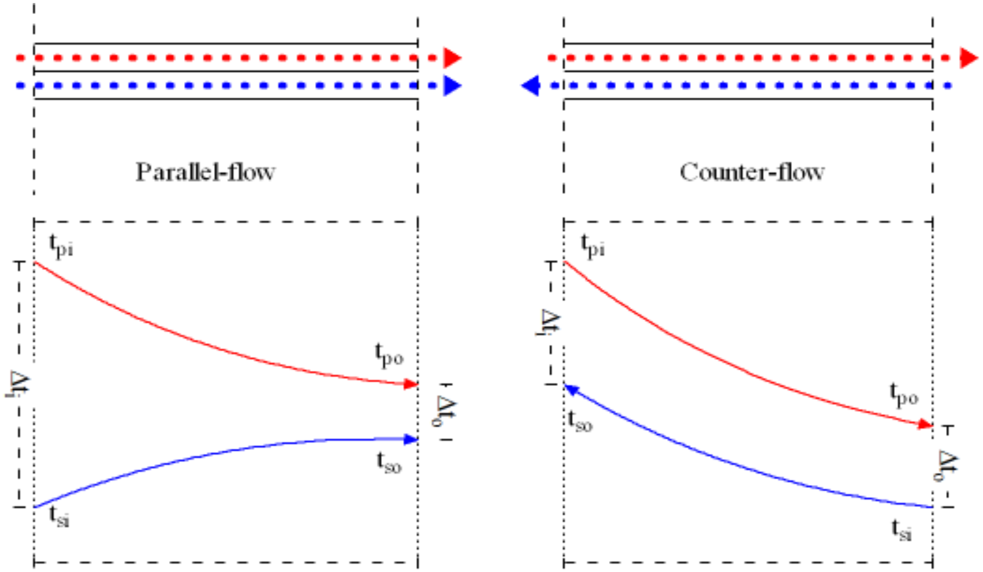
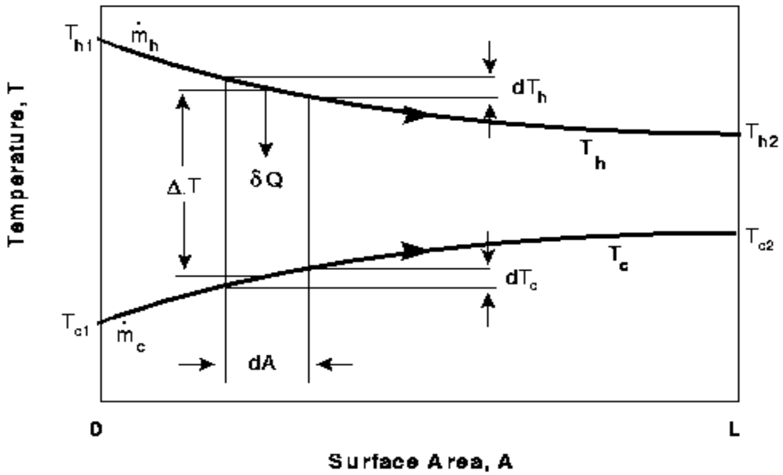
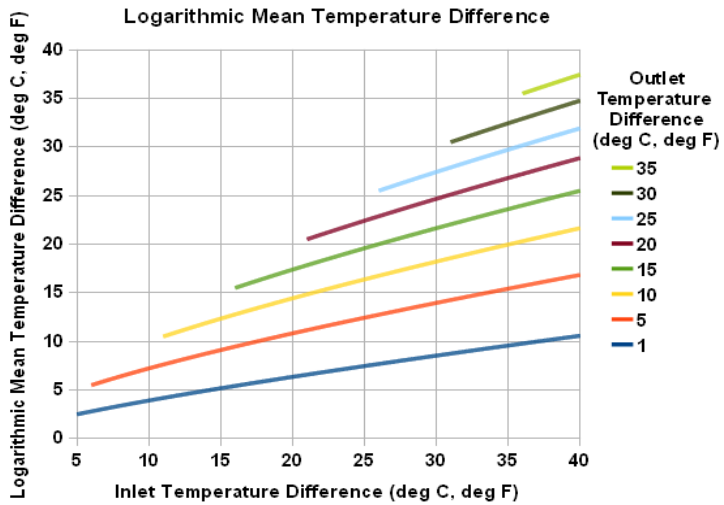
Logarithmic mean temperature







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Electricity production: energy vs exergy efficiency

Geothermal power plant of Soultz-sous-Forêts (Alsace, F):

Electricity from EGS exploitation at 5000 m depth

Leda Gerber, EPFL-LENI

- T at well: 175° C (=$T_{h,in}$)
- T reinjection: 70° C (=$T_{h,out}$)
- Flow rate: **35 l/s**

(LMT$_h$=120C = 393 K)

(take T_a as 15C)

⇒ Heat flux Q = massflow * Cp * ΔT
= 35 (kg/s) * 4184 (J/kg.K) * 105 (K) =

$$\dot{Q}_{in} \approx 15.4 MW_{th}$$

- Gross electricity production: 2.1 MW_{el}
- Parasitic losses: 0.6 MW_{el}
- Net electricity production: **1.5 MW_{el}**

Carnot factor
= 1 – (T_a/LMT) = 1 – 288/393 = 0.28

$$\eta = \frac{\dot{W}_{cycle}}{\dot{Q}_{in}} = 10\%$$

1st Law: low efficiency!

$$\varepsilon = \frac{\dot{W}_{cycle}}{\left(1 - \frac{T_0}{T_h}\right)\dot{Q}_{in}} = 35\%$$

2nd Law: comparable to thermal power plants

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Importance of T-level

2 liquid resources with 50 kg/s, T_a = 10°C, same ΔT = 50 K:

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$T_{h,in}$ = 200° C
$T_{h,out}$ = 150° C

$T_{h,in}$ = 150° C
$T_{h,out}$ = 100° C

$$\dot{Q}^+ = \dot{m} \cdot c_p \cdot (T_{in} - T_{out}) = 10500\ kW_{th}$$

$C_p(H_2O)$=4184 J/kg/K

Carnot factor $= 1 - \frac{T_a}{\frac{T_{in}-T_{out}}{ln\frac{T_{in}}{T_{out}}}}$, where $\frac{T_{in}-T_{out}}{ln\frac{T_{in}}{T_{out}}} = T_h$

0.368 → max. electricity: 3864 kWe

0.288 → max. electricity: 3024 kWe

- 22 %

Electricity production potential as *f*(*T*)

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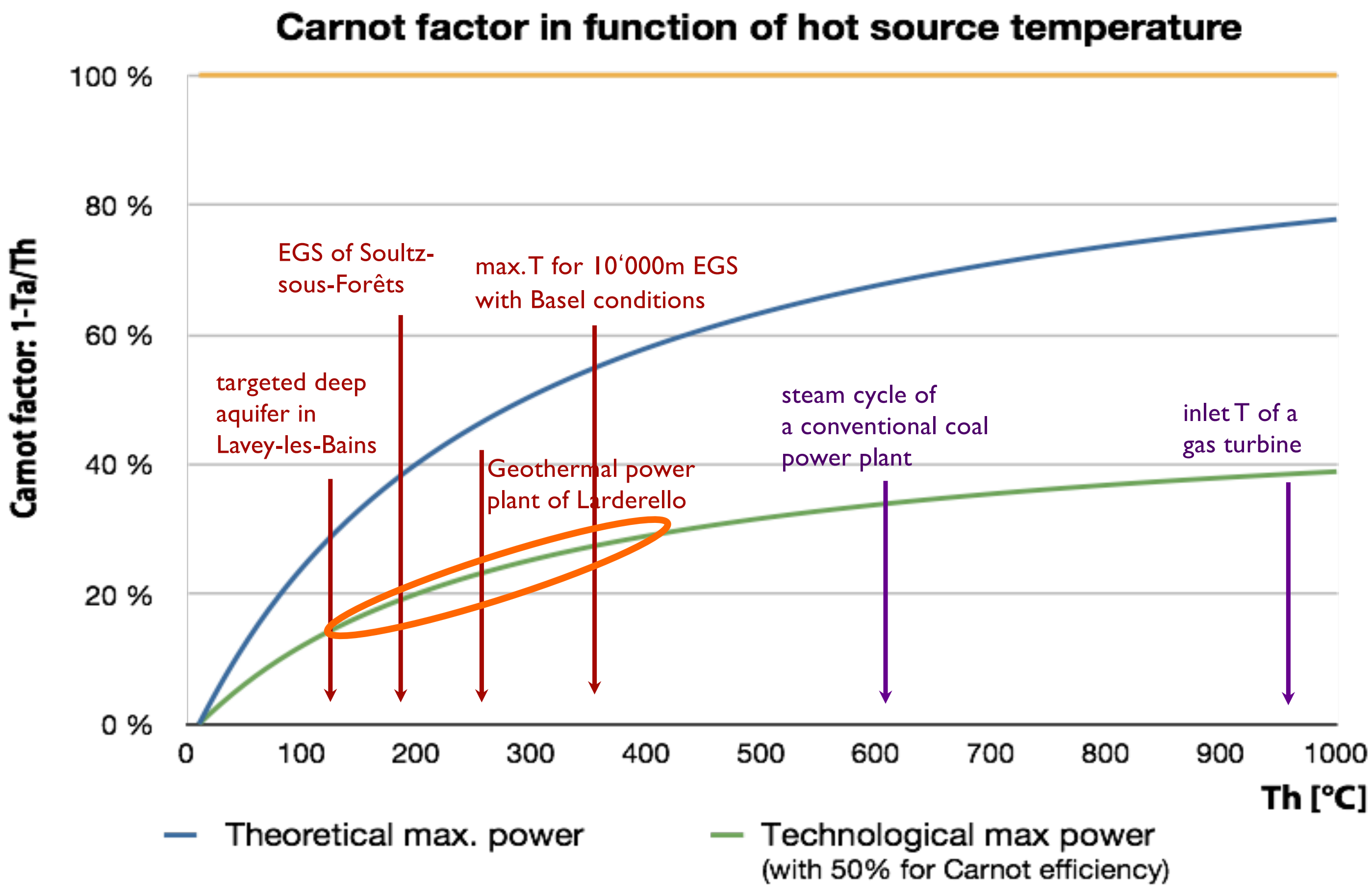
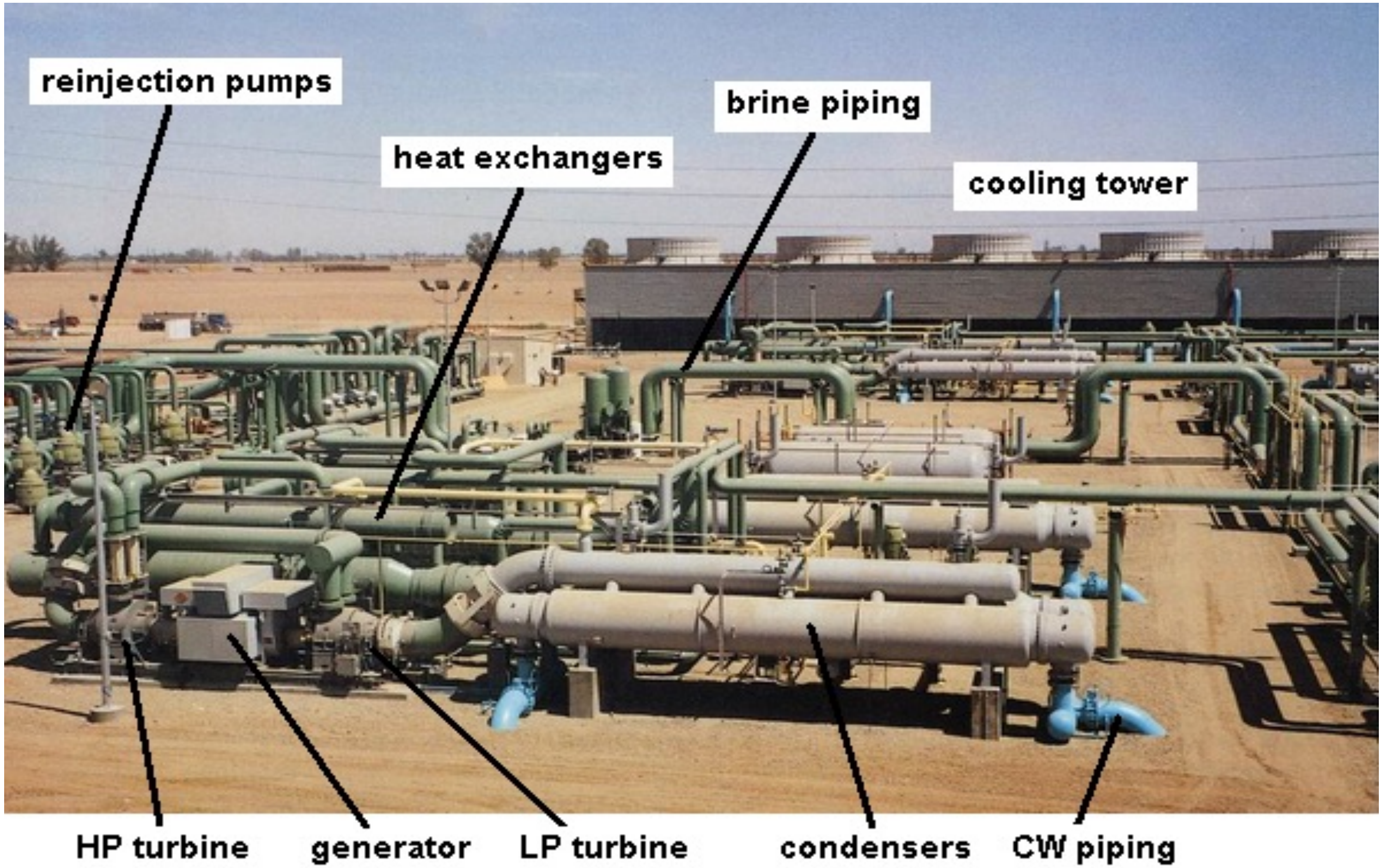


20% = typical 1st law effectiveness

Geothermal plant, aerial view

Ronald DiPippo: Geothermal power plants: Elsevier 2008

Geothermal plant, closer view



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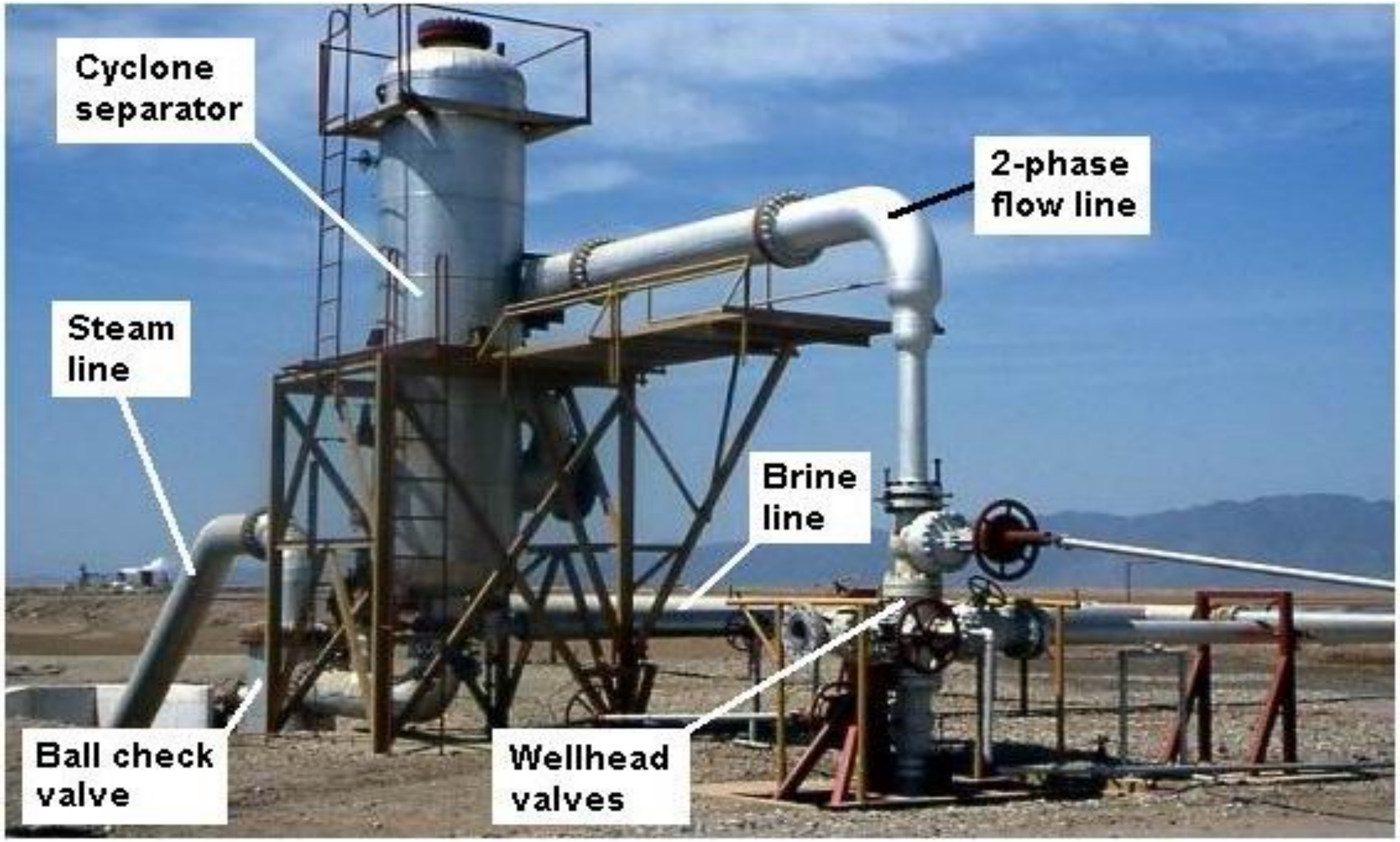
Wellhead view



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Turbine rotor (110 MWe)

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Hatchobaru plant, Japan

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Cerro Prieto (720 MWe), Baja California (Mexico)

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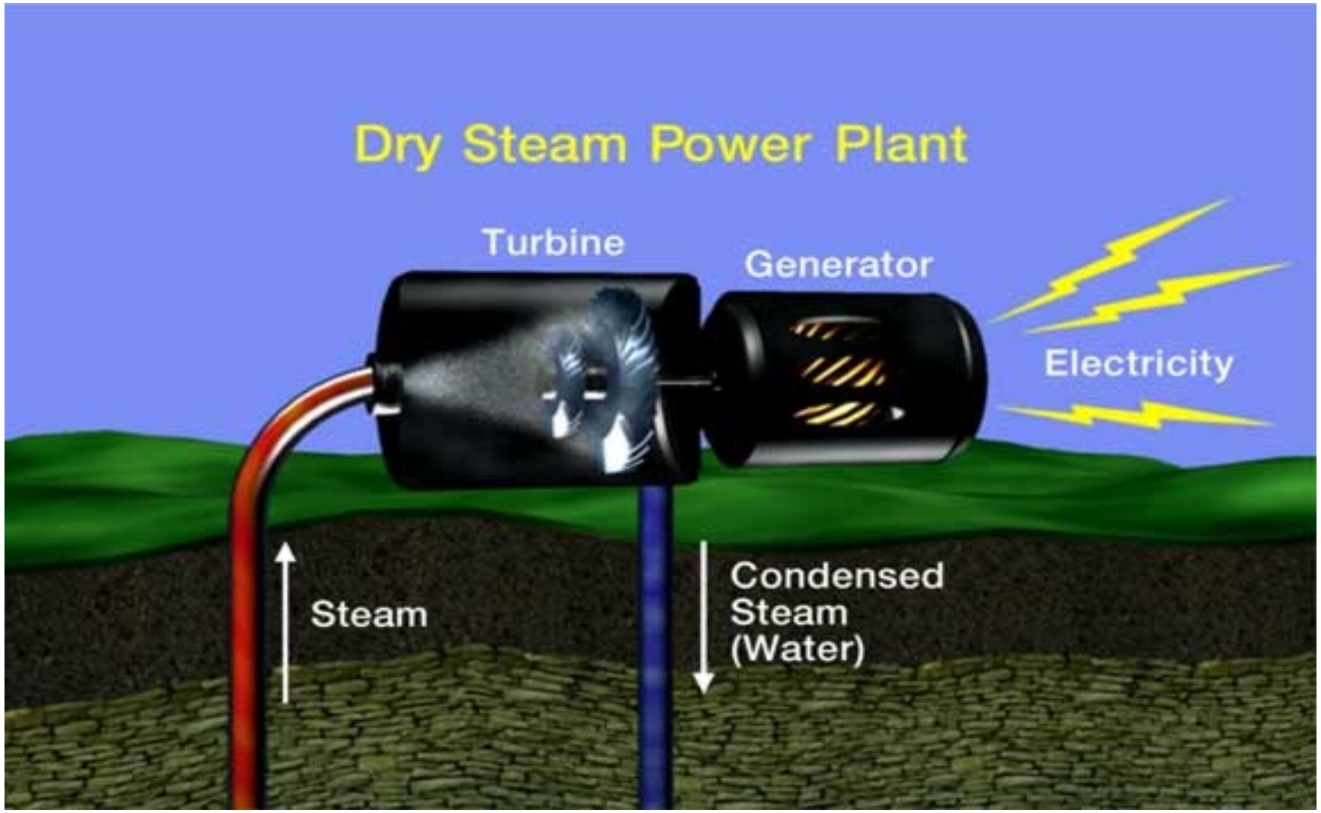
Dry steam power plant

- Steam (not water) shoots up the wells directly into a turbine.
  Dry steam fields are relatively *rare*.



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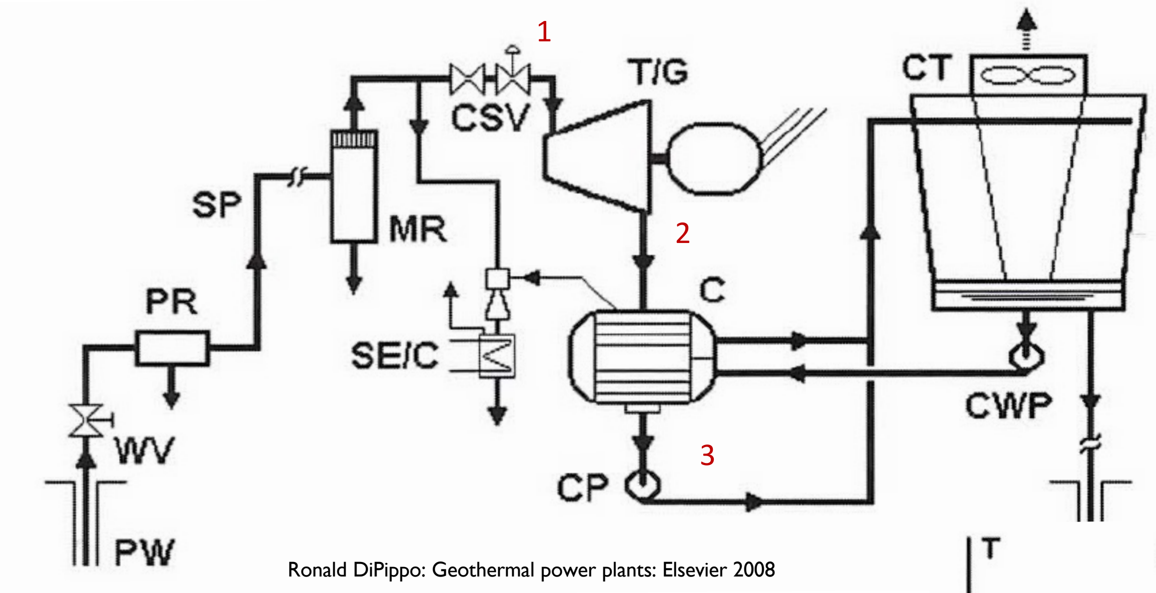
Dry steam power plant

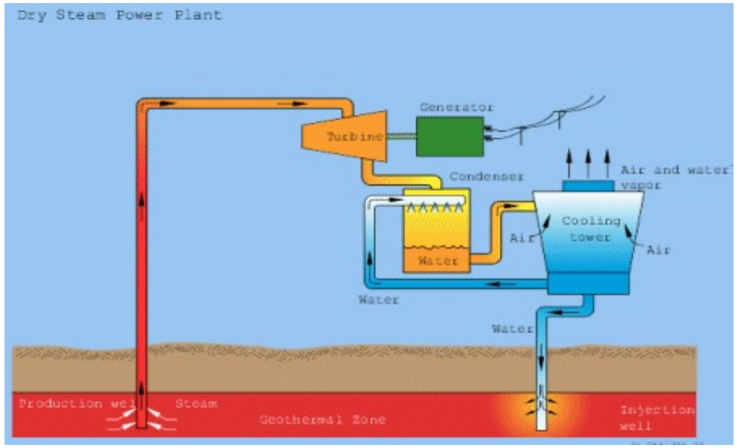
- The Geysers dry steam field, northern California, the 1st USA geothermal power plant (1962) and among the world's largest (1 GW_{el} average).

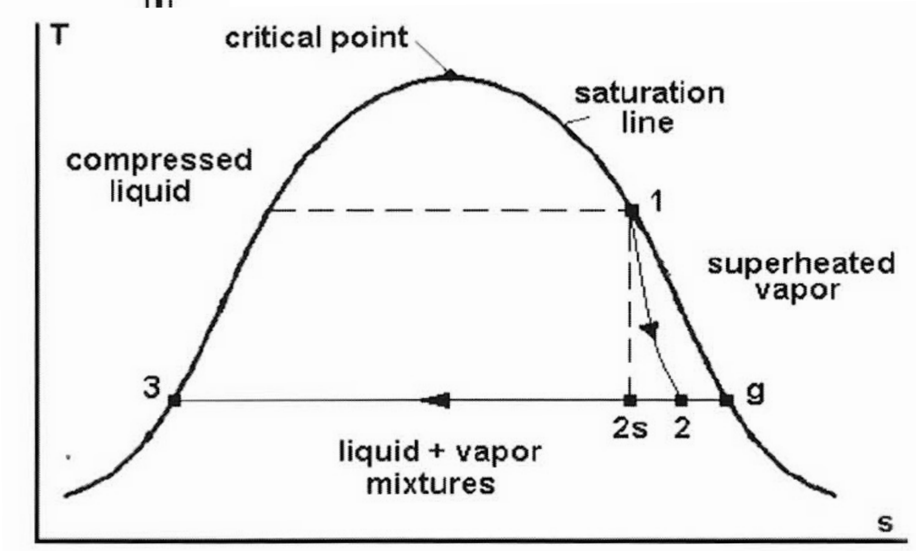
Dry steam power plant



production well (PW)
wellhead valve (WV)
particulate remover (PR)
steam piping (SP)
moisture remover (MR)
control & stop valve (CSV)
turbine with generator (T/G)
steam ejector/condenser (SE/C)
condenser (C)
condensate pump (CP)
cooling tower (CT)
cooling-water pump (CWP)
injection well (IW).

Ronald DiPippo: Geothermal power plants: Elsevier 2008





Flash steam plant

- Flash technology was invented in New Zealand. Flash steam plants are common, since most reservoirs are hot (pressurized) water reservoirs.

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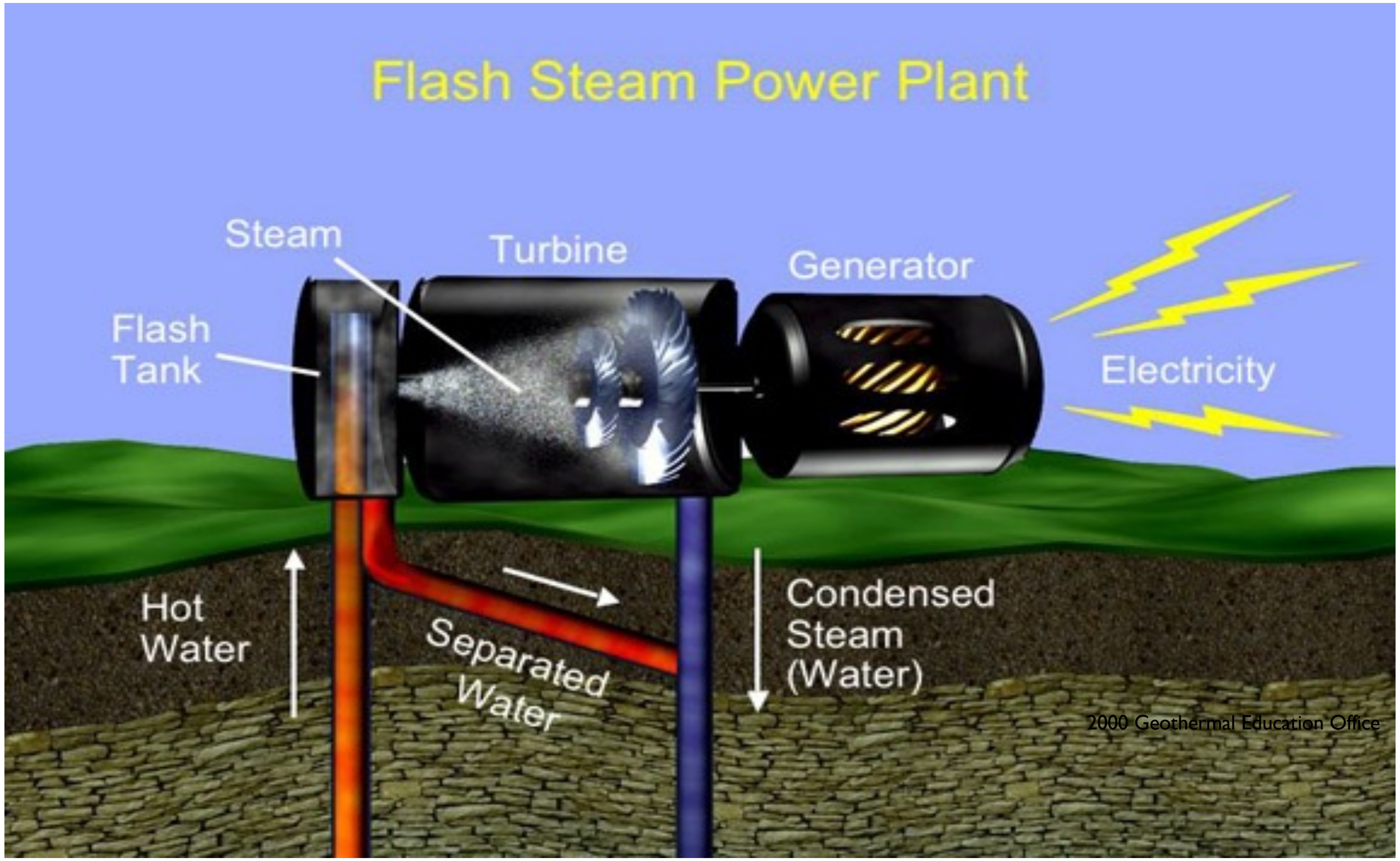
Flash steam power plant

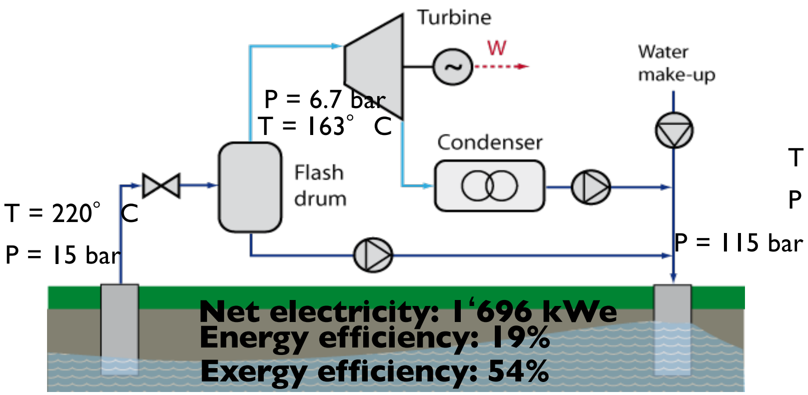
- As hot water is released from the high pressure of the deep reservoir in a flash tank, some of it (30-40%) flashes explosively to steam.



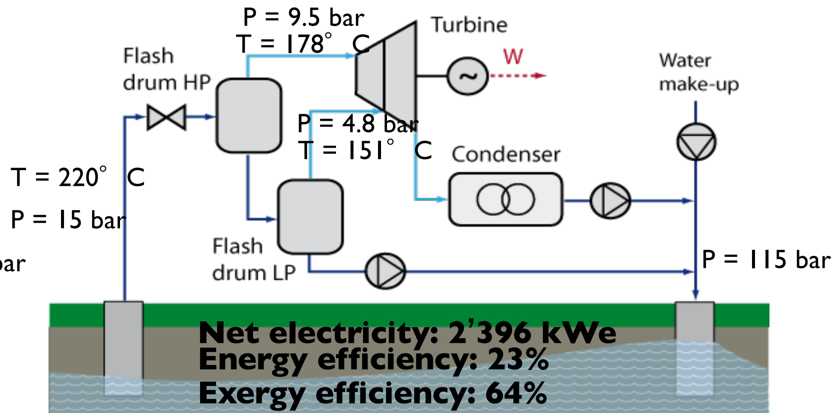
Flash conversion cycles

Leda Gerber, EPFL-LENI

- Direct use of the geofluid (=liquid, or mixture of gas and liquid)
- Separation between liquid and gas (power from steam turbine)
- Temperature lower limit: 150-180°C
- Quality of the geofluid is critical (dissolved minerals!)



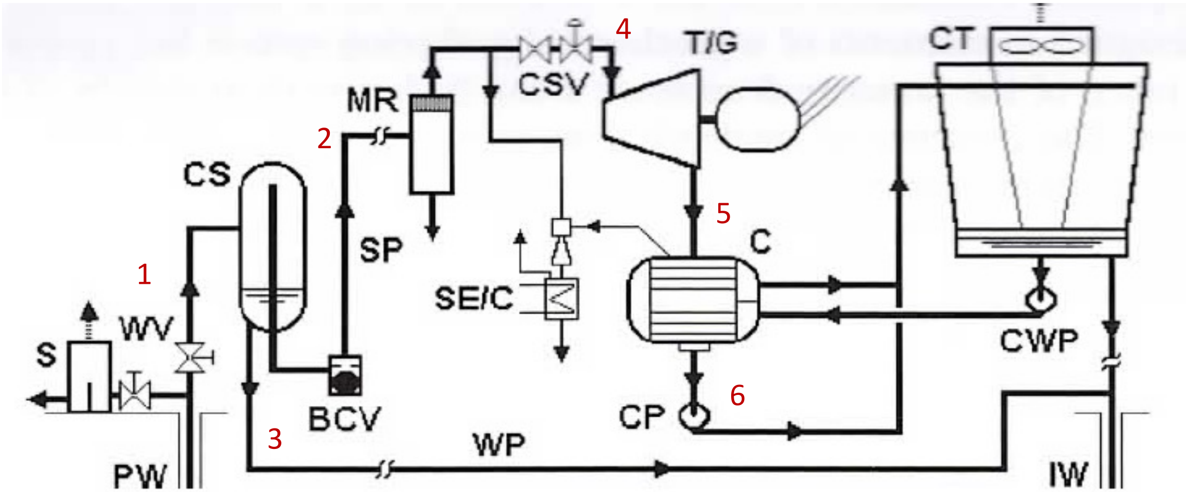
Single-flash system



Double-flash system
Additional power generation
More expensive

Single-flash schematics

silencer (S)
cyclone separator (CS)
ball check valve (BCV)
water piping (WP)
steam ejector/condenser (SE/C)



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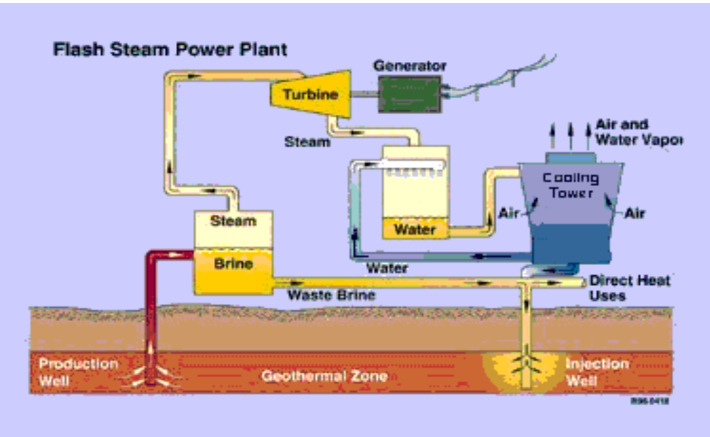
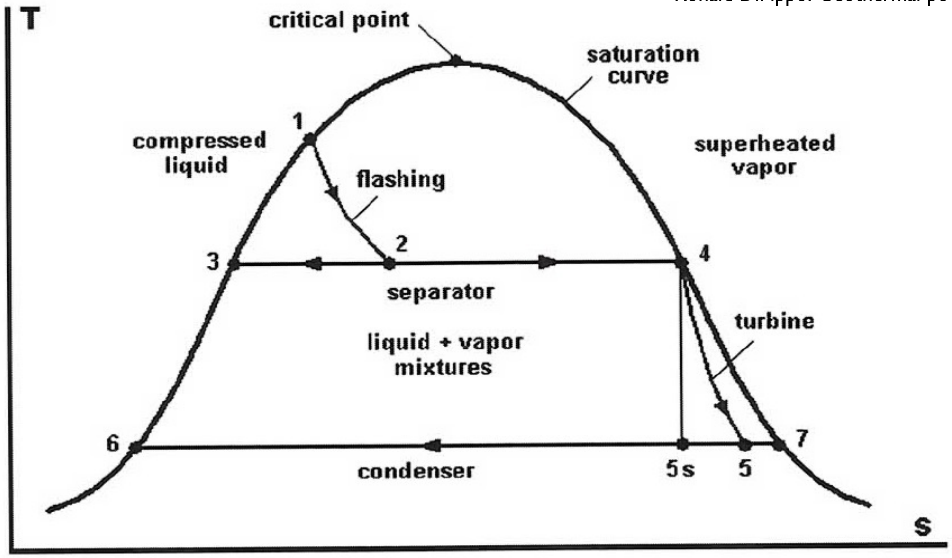
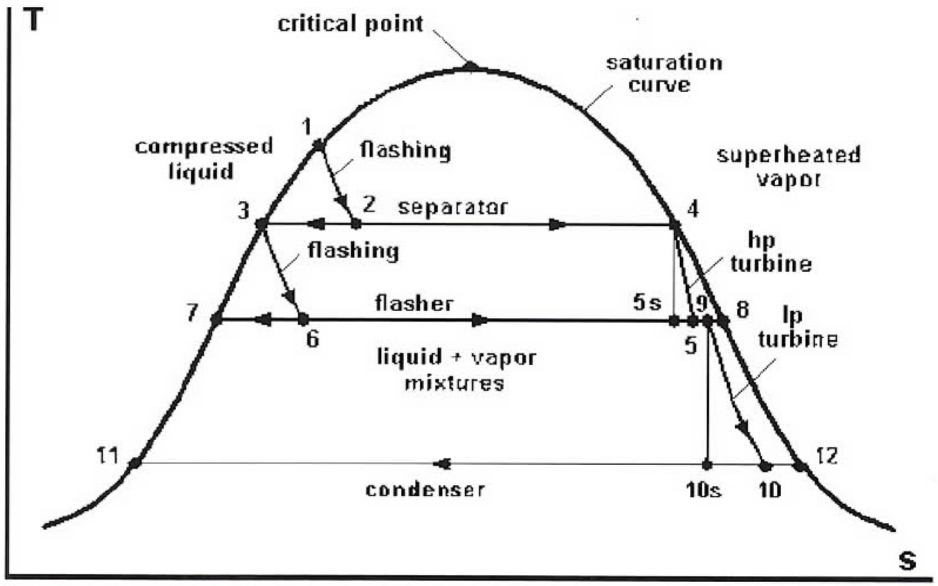
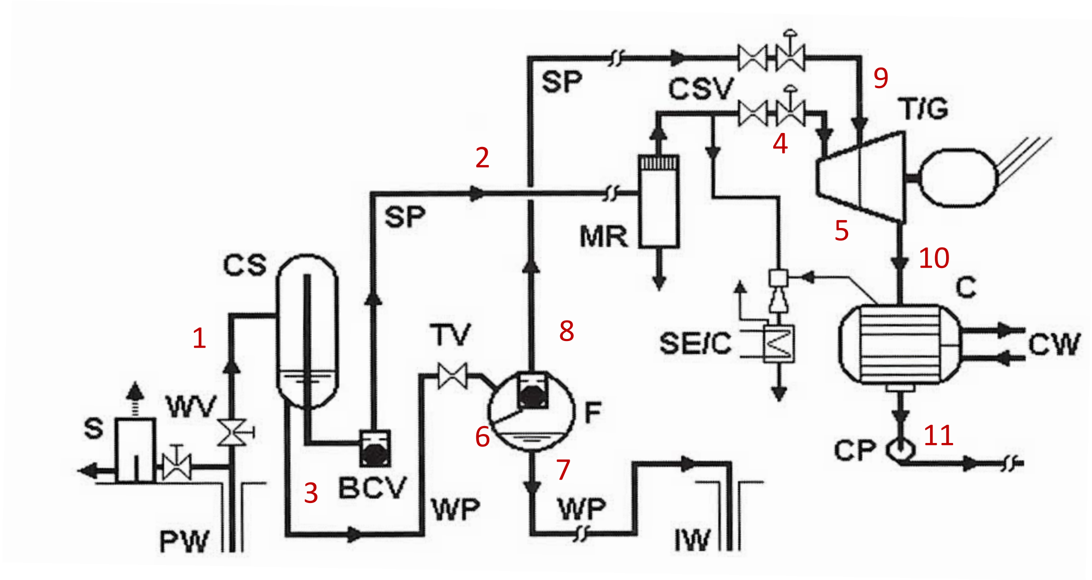




Double-flash schematics





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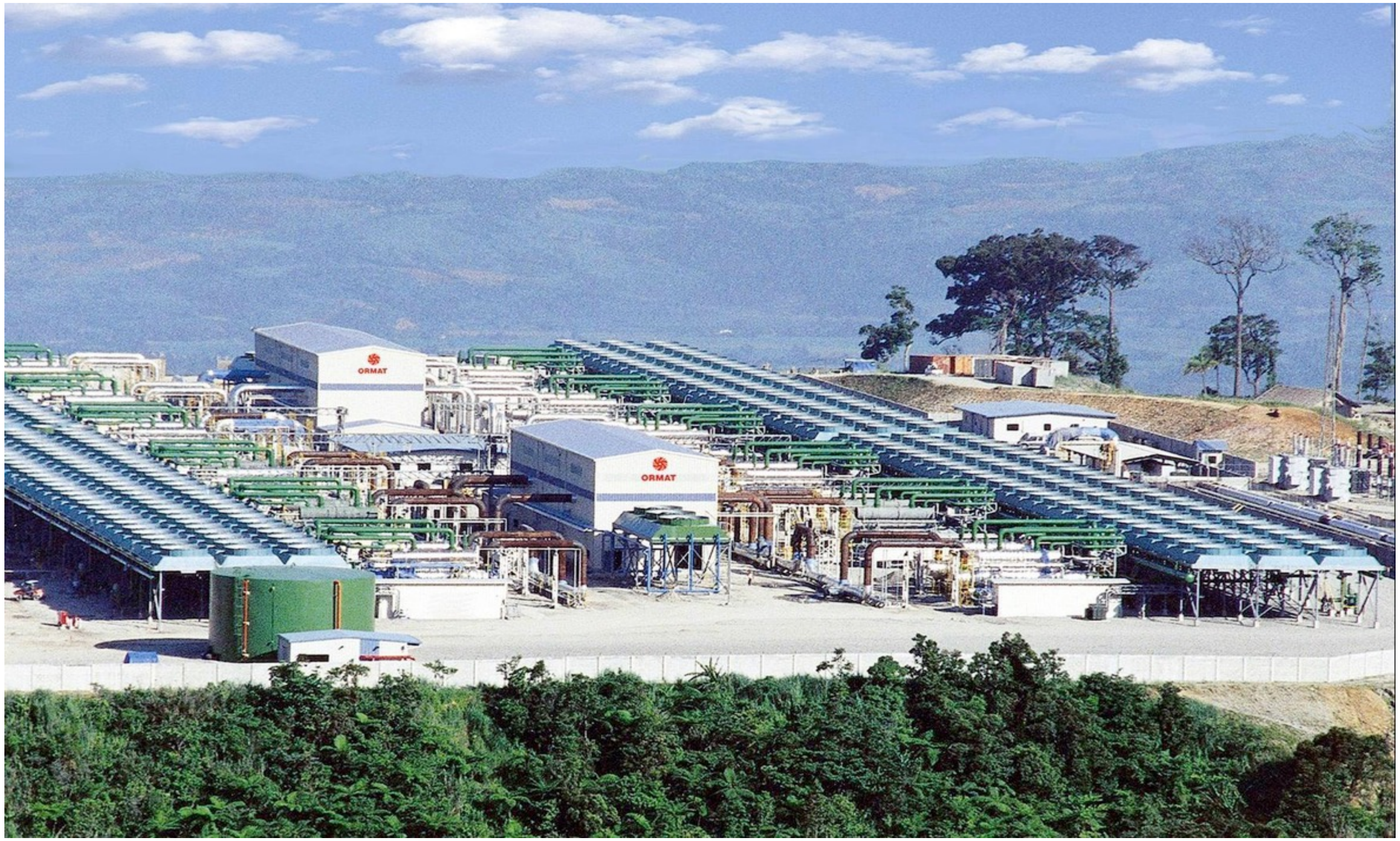
Flash Binary Plant, Upper Mahiao (125 MWe)



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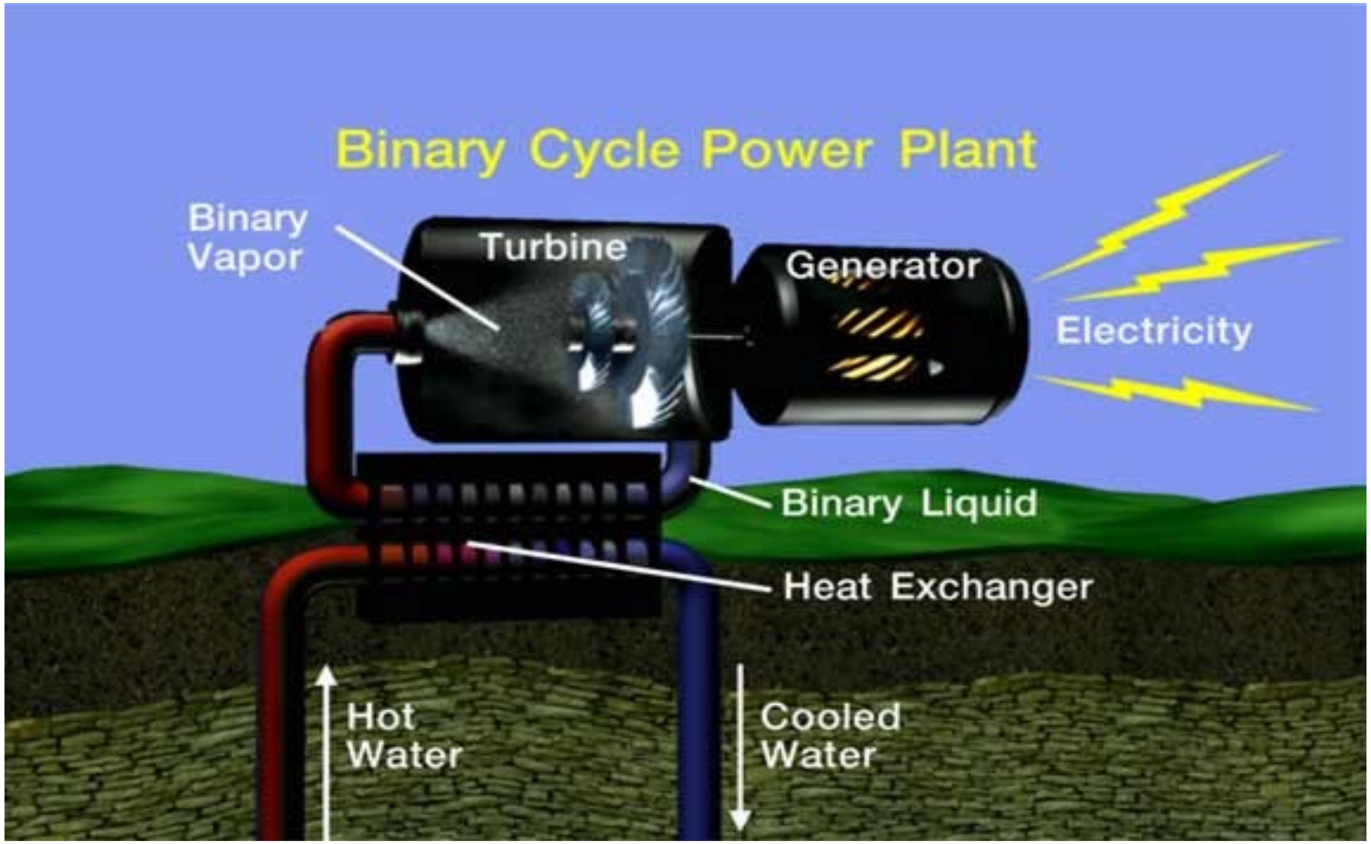
Binary cycle power plant

- Heat from the geothermal water is used to vaporize a working fluid in a 2nd network This vapor powers the turbine.



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Binary conversion cycles

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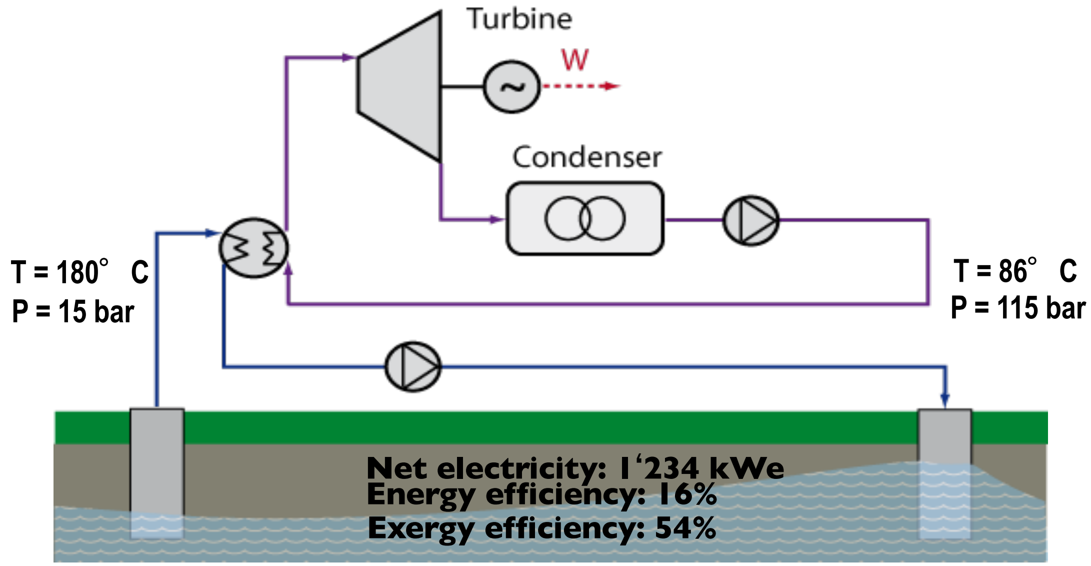
- Heat transfer occurs between the geofluid and a secondary fluid
- Use of organic fluids (**Organic Rankine cycles - ORC**) or mixture of water and ammonia (**Kalina cycles**)
- Temperature lower limit: 70-90°C (uses exist up to 200°C)
- No emissions of geofluid to atmosphere



Combined conversion cycles

To increase the electrical efficiency :

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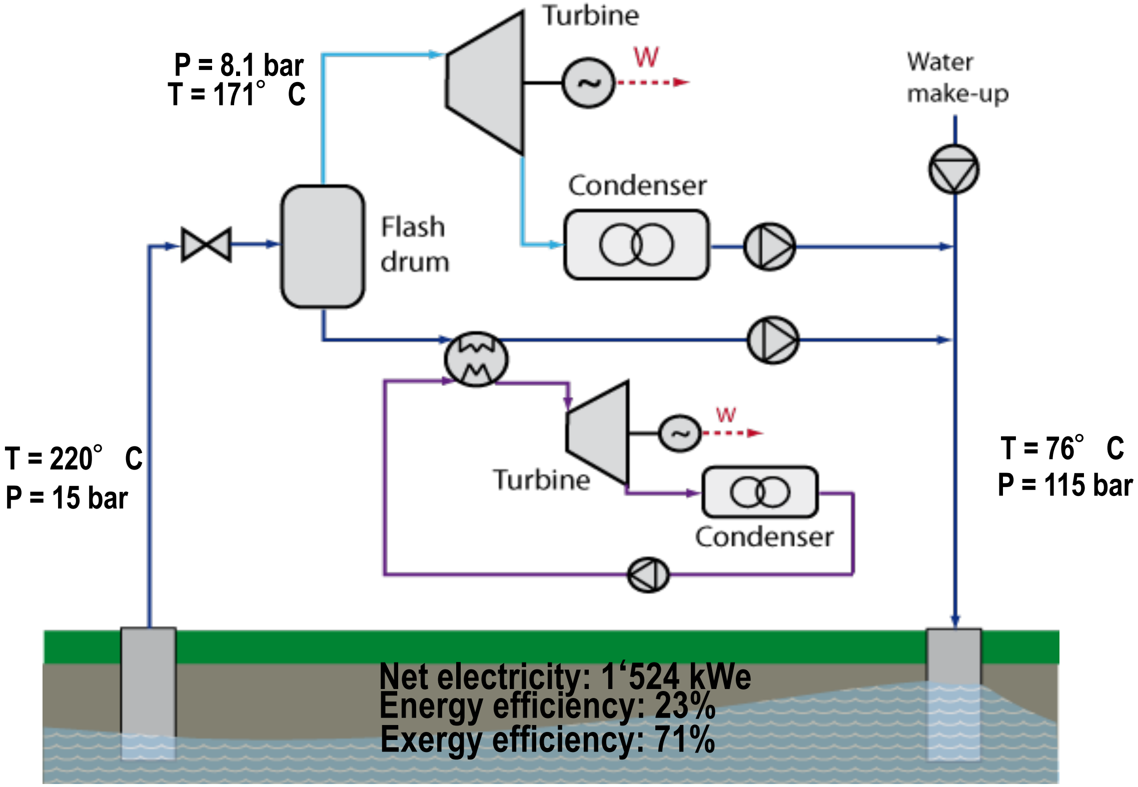
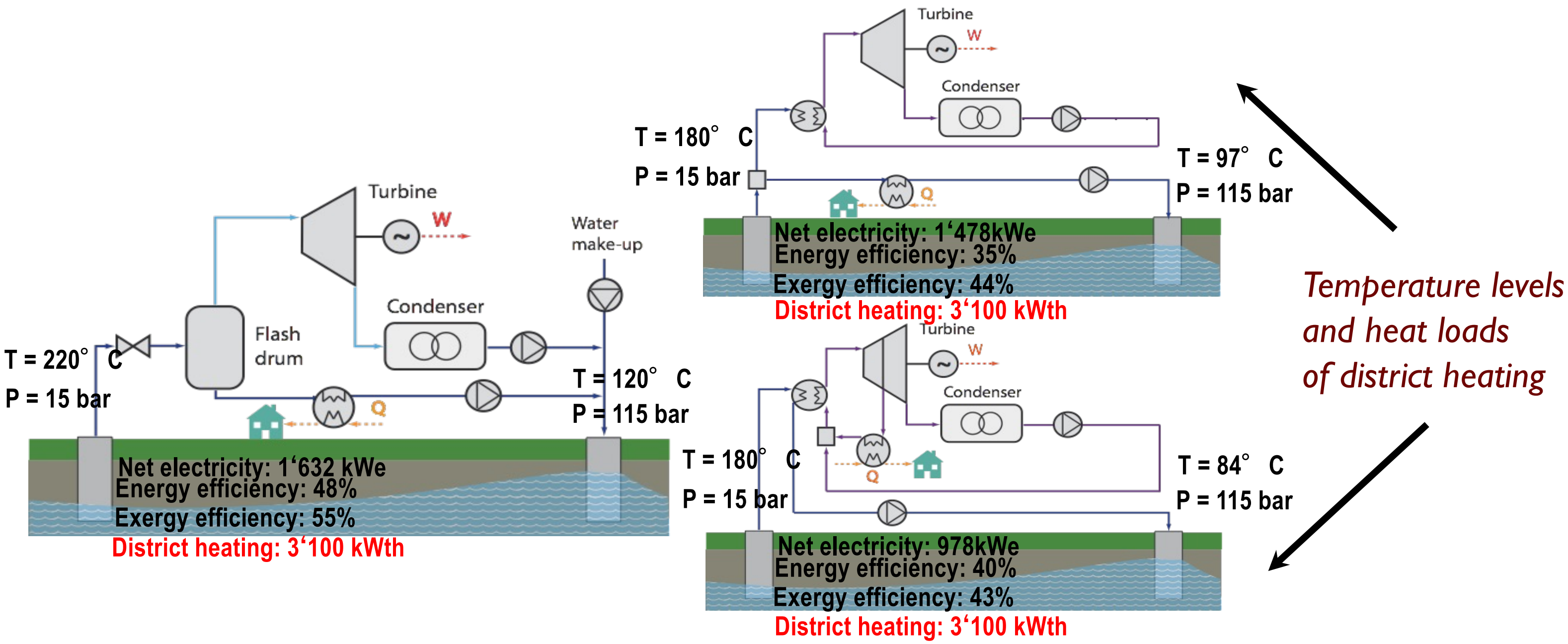
– Flash system with <u>bottoming ORC</u>



Cogeneration with conversion cycles

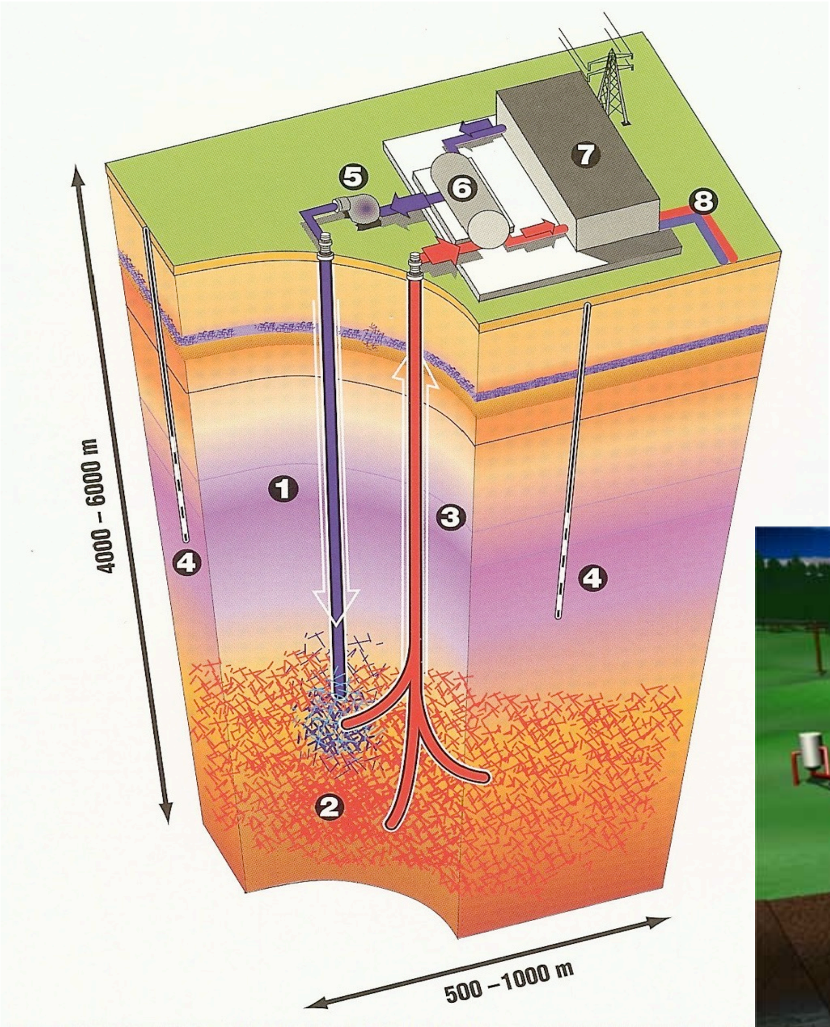
Effects on energy and exergy efficiency

- Increase due to the **use of waste heat** (flash systems)
- Trade-off between electricity and heat production (binary cycles)

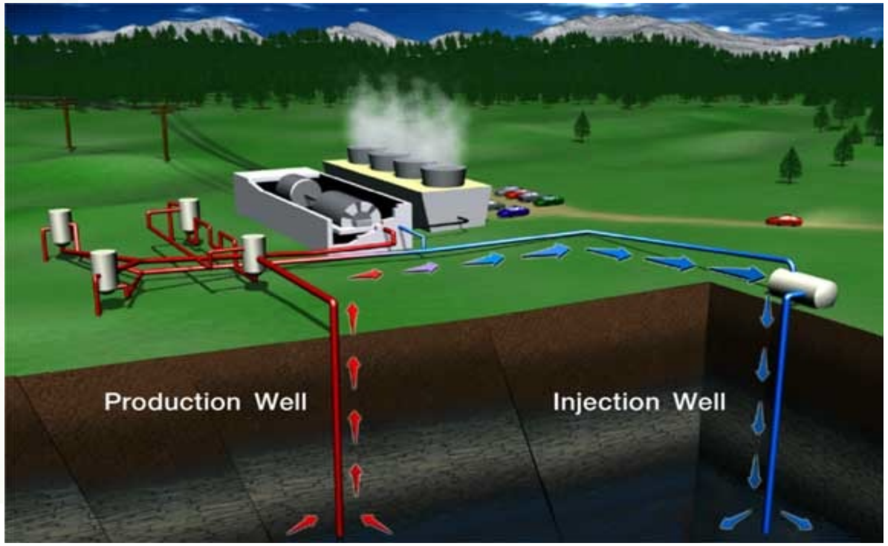


Hot *dry* rock (HDR) – or Deep Heat Mining (DHM)

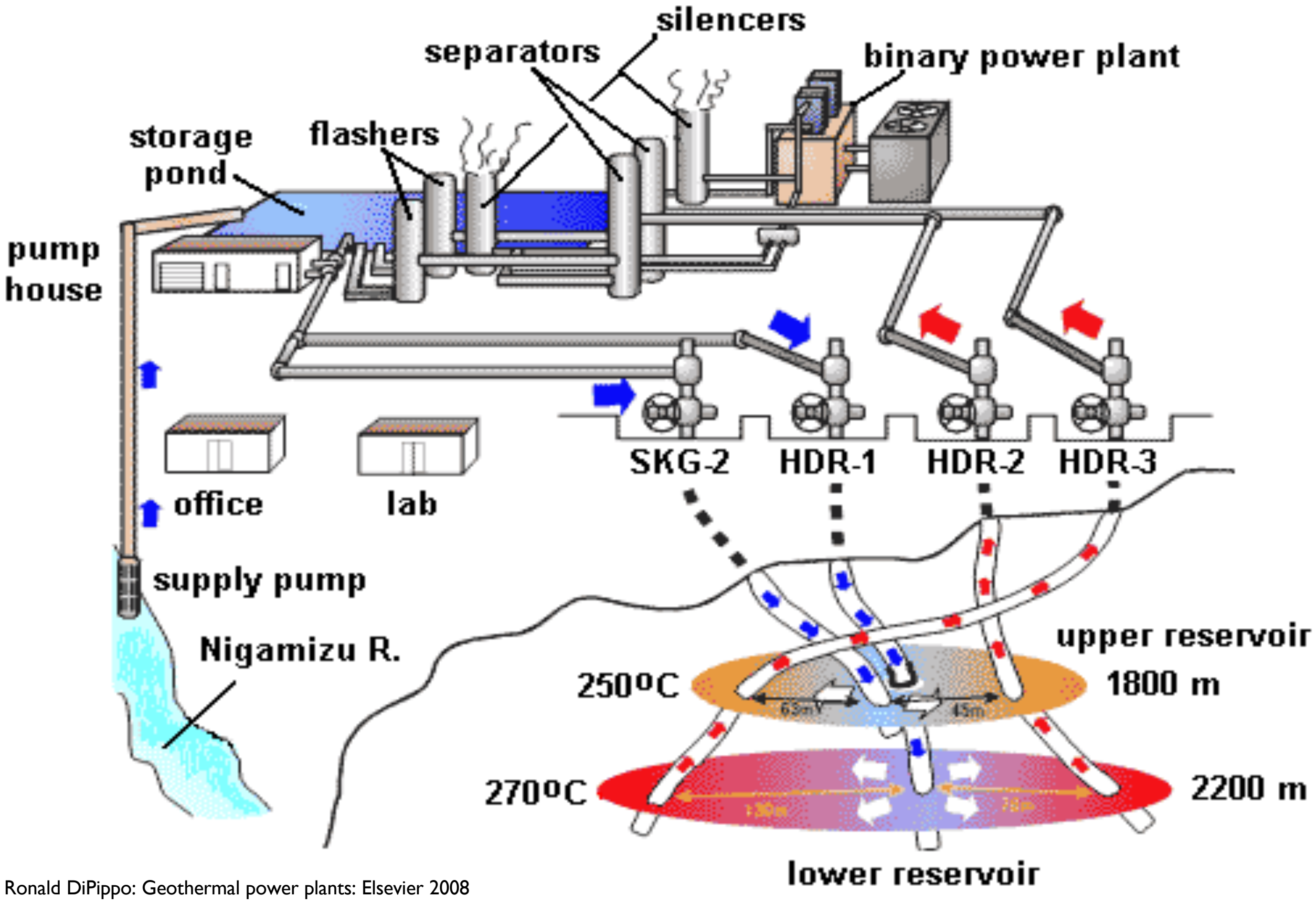
→ *unsustainable*



1. Injection well
2. Fissured rock
3. Production well
4. Control wells
5. Pump
6. HEX
7. Plant
8. District heat



HDR, Hijiori, Japan



Ronald DiPippo: Geothermal power plants: Elsevier 2008

Temperature level usage

Electricity generation
Heat (industry, buildings)
Cogeneration

Enhanced Geothermal Systems

EGS :

3'000 - 10'000m*

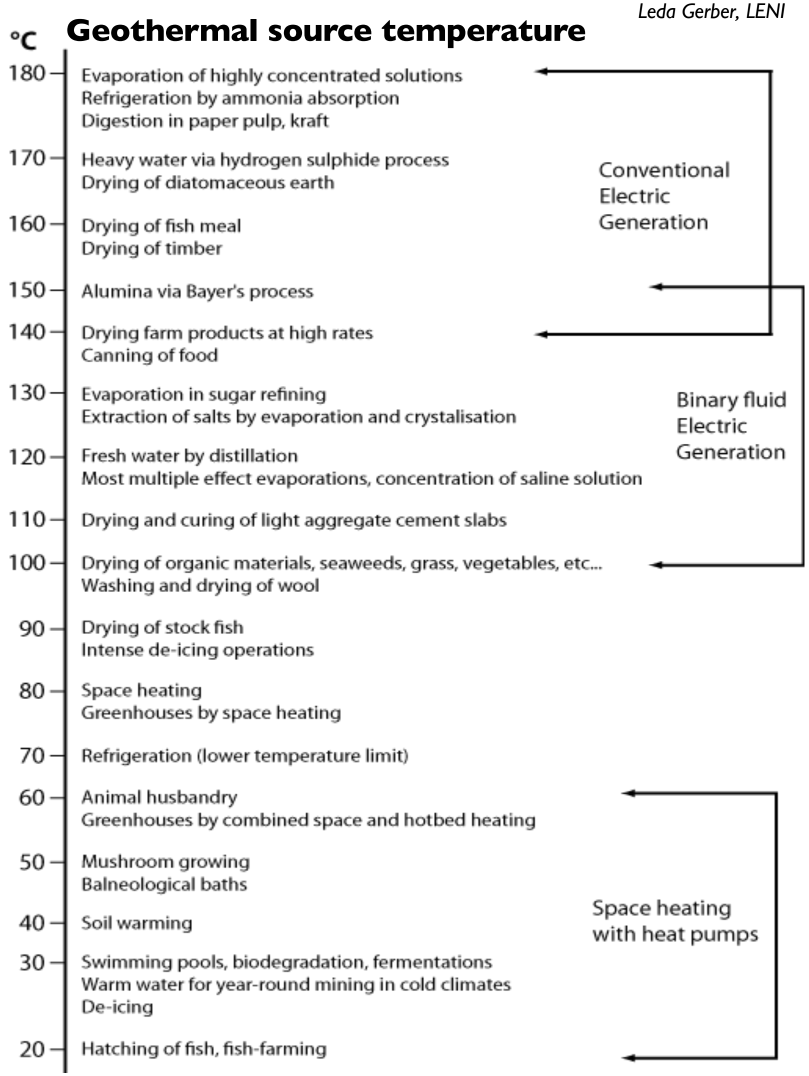
90 - 350 ° C

http://www.youtube.com/watch?v=vhSGKIrlVuw

Direct heat use

Heat pumps for building heating

Leda Gerber, LENI



•J. Tester et al, *The Future of Geothermal Energy – Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st century*, MIT technical report, 2006

Geothermal reality for heat use

Installed capacity (MW)

28% Direct heat use
72% Heat pumps

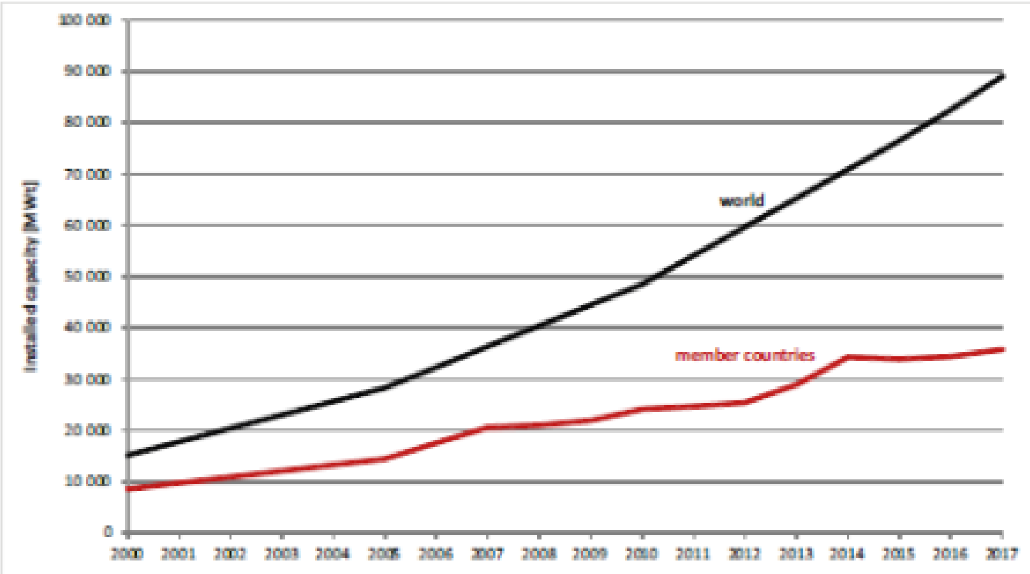


Figure 10: Installed capacity [MW] of all geothermal heat uses (direct use and GHP use) in member countries and worldwide 2000 - 2017. *Member country data: IEA Geothermal Annual Reports 2007, 2008 and 2009, and WG 10 country reports 2010 to 2017; world data: Lund & Freeston, 2001; Lund et al., 2005 and 2011; and Lund & Boyd, 2016; 2015-2017: estimated assuming a compound annual growth rate of 7.9%.*

Heat use GWh/yr

40% Direct heat use
60% Heat pumps

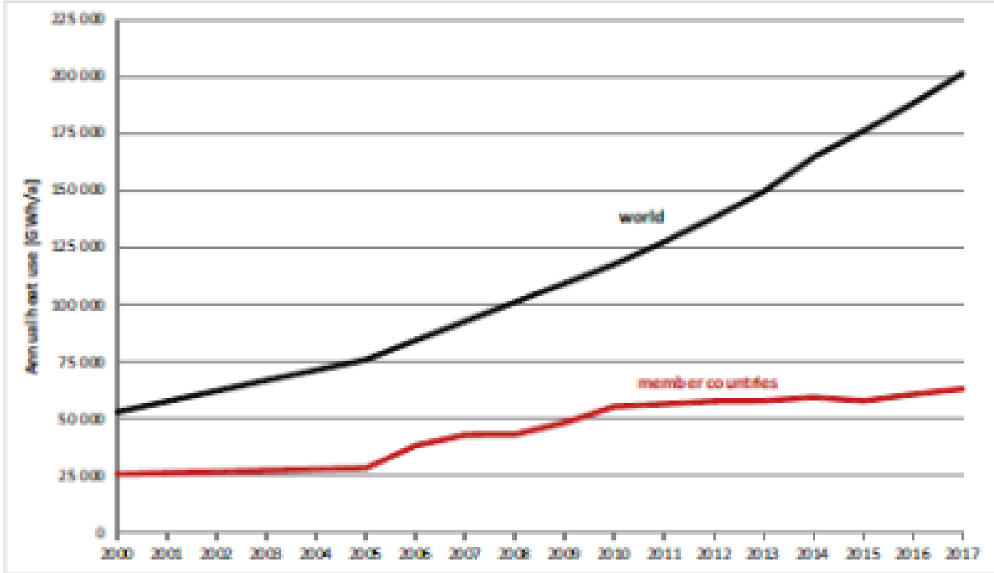


Figure 11: Annual heat use [GWh/a] of all geothermal heat uses (direct use and GHP use) in member countries and worldwide 2000 - 2017. *Member country data: IEA Geothermal Annual Reports 2007, 2008 and 2009, and WG 10 country reports 2010 to 2017; world data: Lund & Freeston, 2001; Lund et al., 2005 and 2011; and Lund & Boyd, 2016; 2015-2017: estimated assuming a compound annual growth rate of 6.9%.*

Direct heat use: district or space heating, bathing, heating of greenhouses, snow melting, aquaculture/fish farming or industrial applications, etc.

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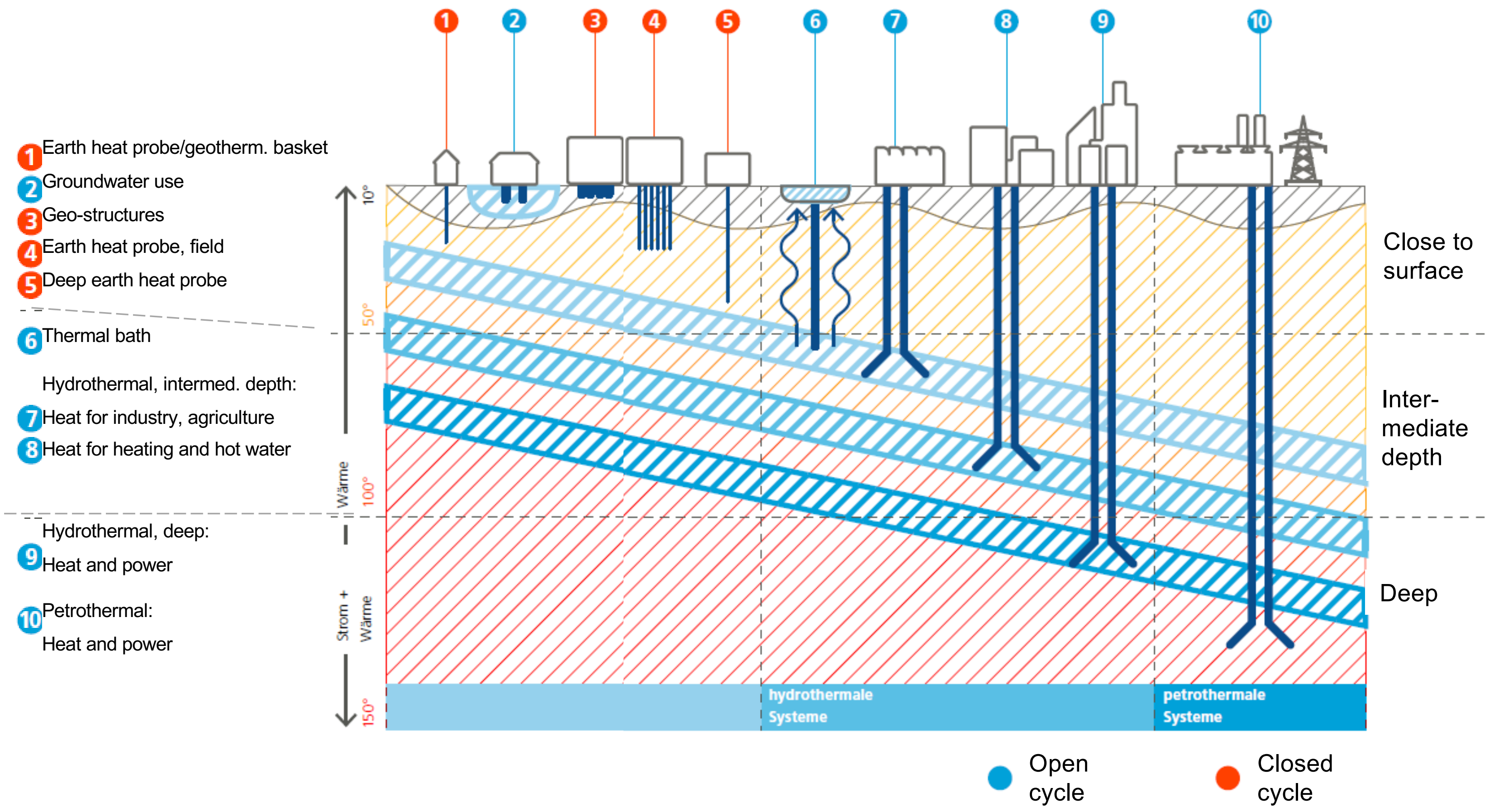
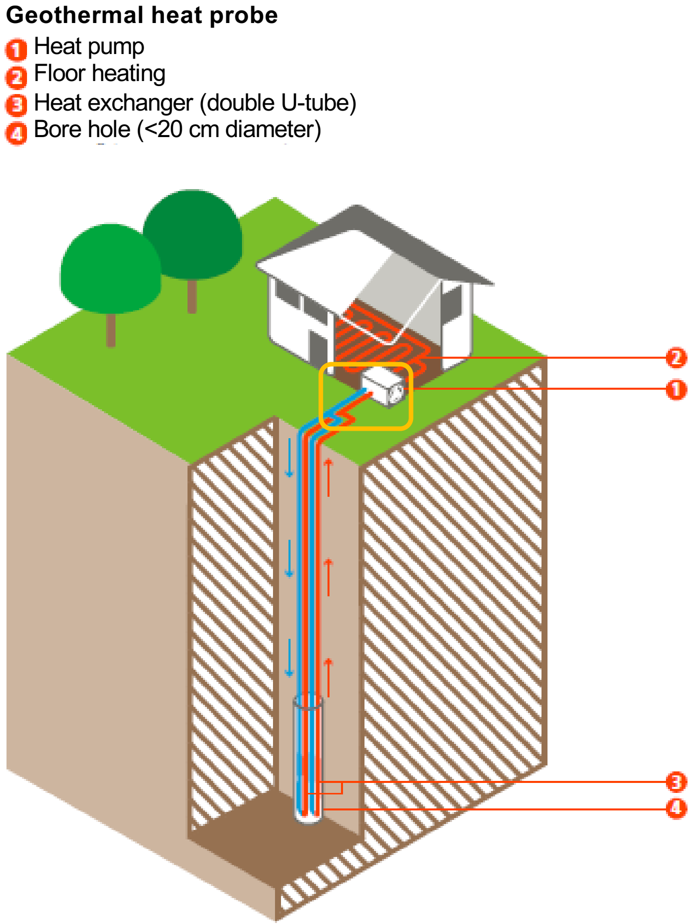
Different forms of geo-energy application

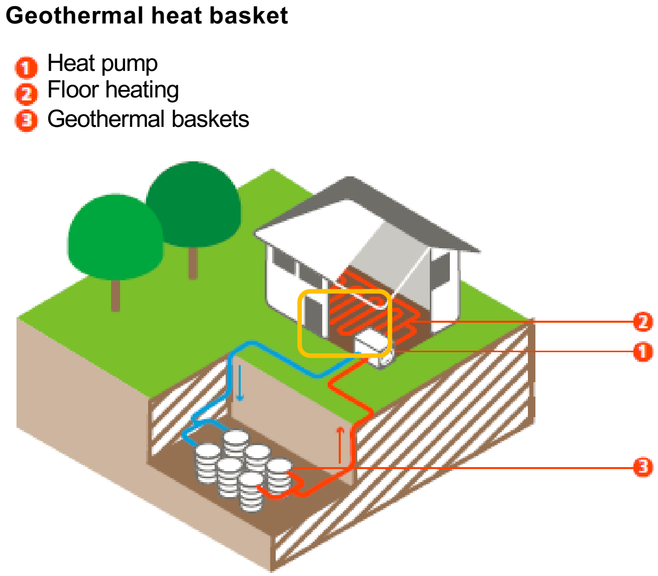


Energie Schweiz: Geothermie in der Schweiz, 2006

Close to the surface

- Residential application with heat pump (80% of Swiss geothermal energy use):



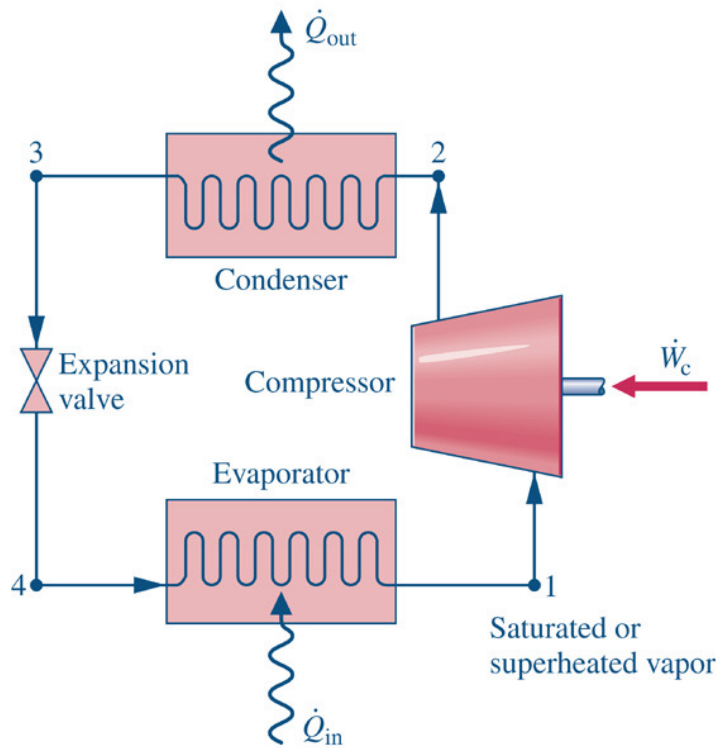


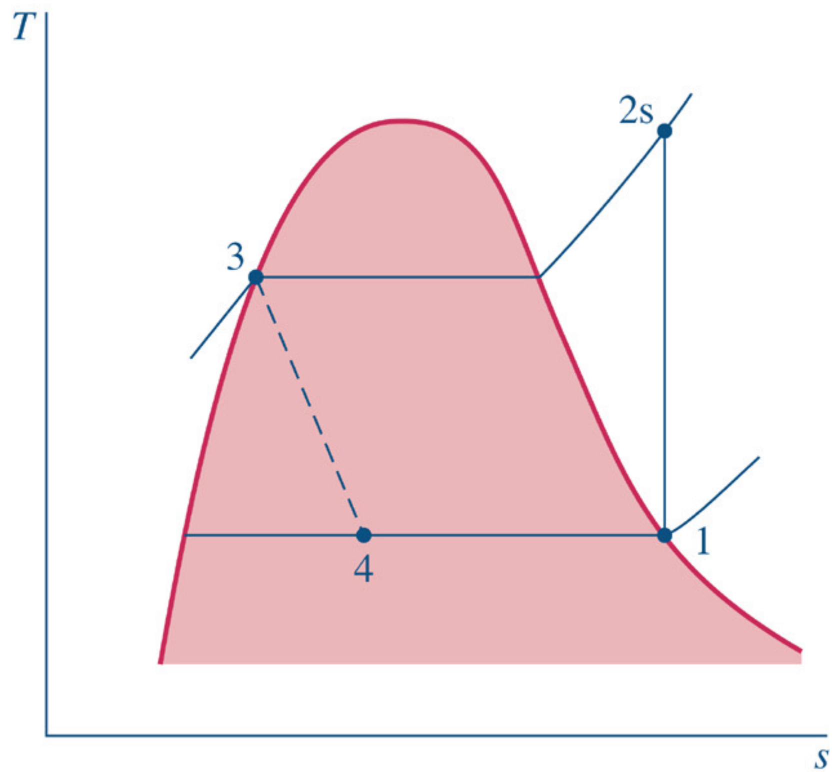
Depth:
1.5 to 4 m for geothermal baskets
50 to 250 m for heat probe

Temperature: 5-20°C

Heat pump systems

- Vapor-compression heat pumps:





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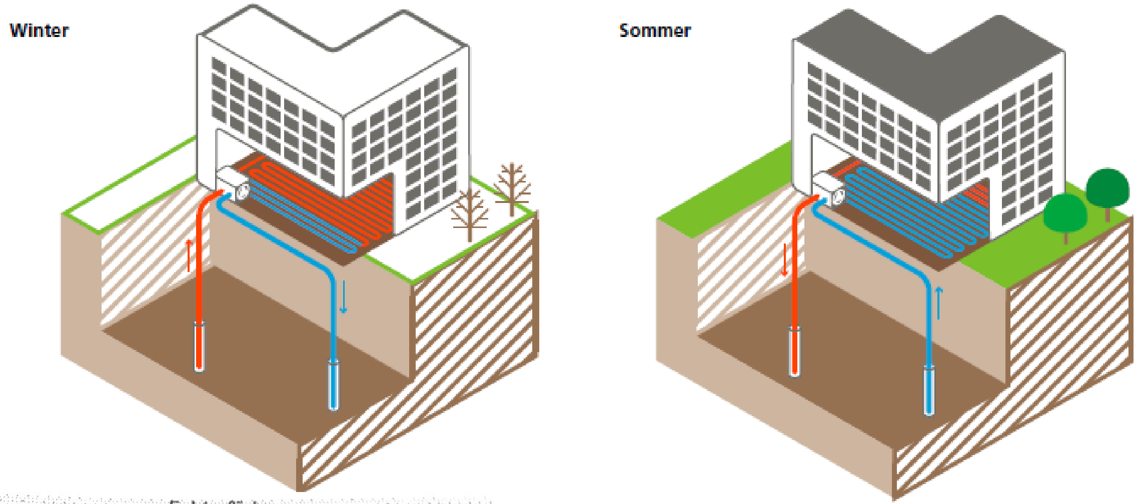
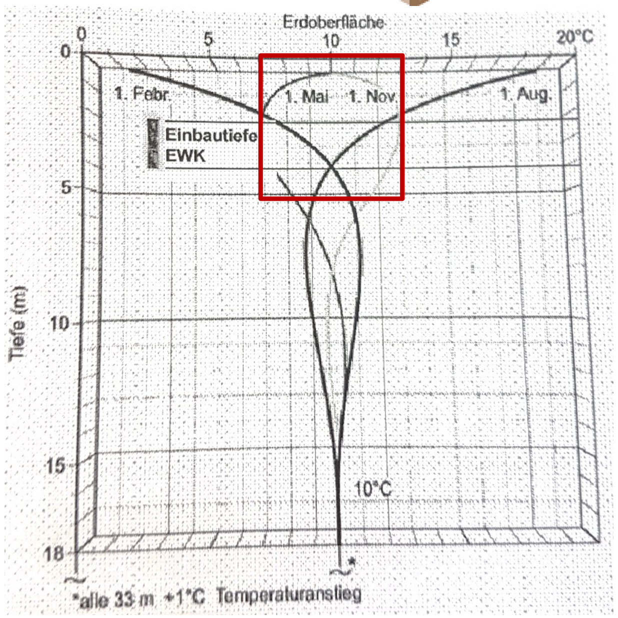
Close to the surface

- Year around:





- Temperature for geothermal baskets between 7 and 13°C all year
- Phase lag results in warmest temperature in November (→largest heating demand)
- Cooling possibilities in summer

Intermediate depths

From:

- Thermal springs (natural springs)
- Tunnels (groundwater)
- Hydrothermal (aquifers), depth 0.5-3 km

Temperature range: 20-100°C

Use:

- Thermal baths, swimming pools
- Industry: drying, evaporation of concentrated solutions, chemical extraction, deicing (streets)
- Agriculture: drying, green houses, fish farms

In 2015: 75 TWh thermal energy used in direct applications

the tropical house in Frutigen (BE) uses the warm water from the Lötschberg tunnel for breeding sturgeons and cultivating exotic fruits

Klamath Falls, Oregon, a geothermal district-heating system keeps the sidewalks clear and dry at the Basin Transit station after a snowfall

Geothermally powered greenhouses at Gufudalur, Hveragerði

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Summary

- Geothermal **power** plants are clean, reliable and provide **baseload** for decades or centuries, on sites with *thermal anomalies* (volcanic, tectonic), up to 1 GWe of power for the largest sites
- Elsewhere, smaller individual plants may be used (**1-5 MWe**)
- Usually, steam cycles are employed; to exploit low temperature reservoirs for electricity generation, **ORCs** can be used
- 1st law efficiency is rather poor (<20%) but 2nd law efficiency high (>50%)
- Exploitation for **thermal** energy is interesting and more widely used