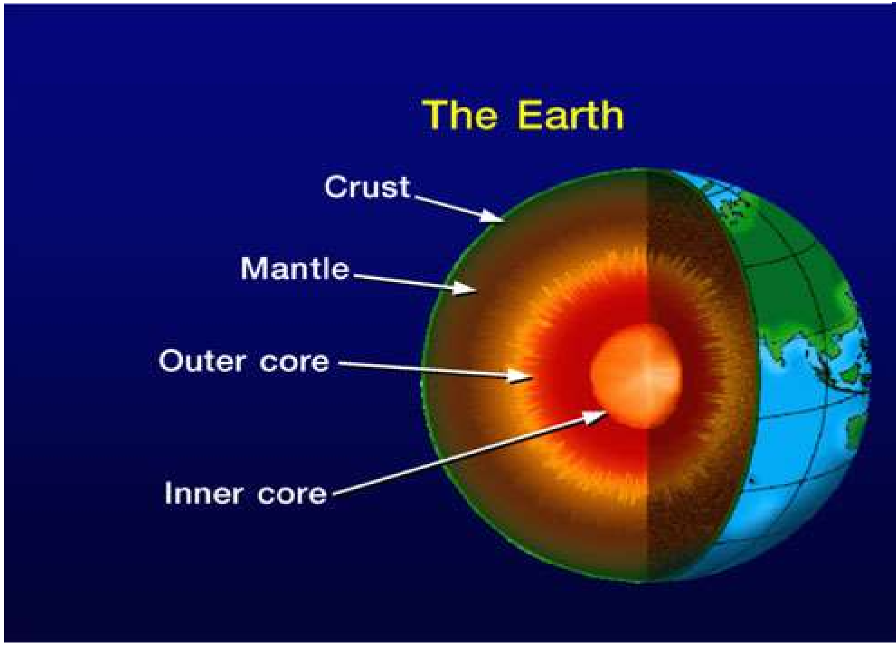
Geothermal energy

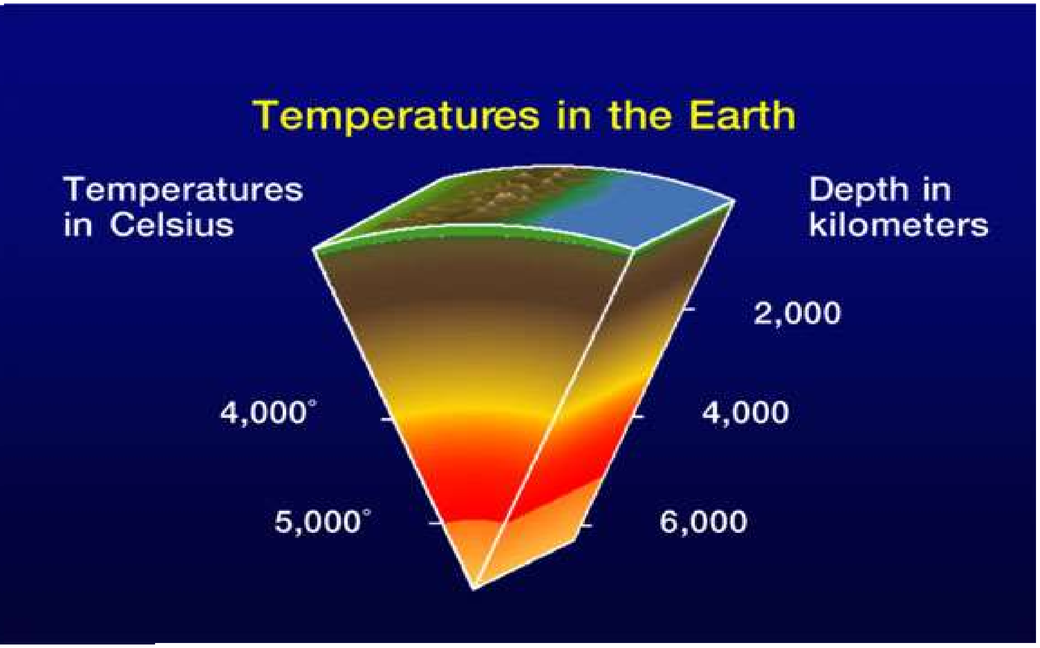
Learning outcomes of todays lecture

- 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)

    (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/dm3]
Ground	0		
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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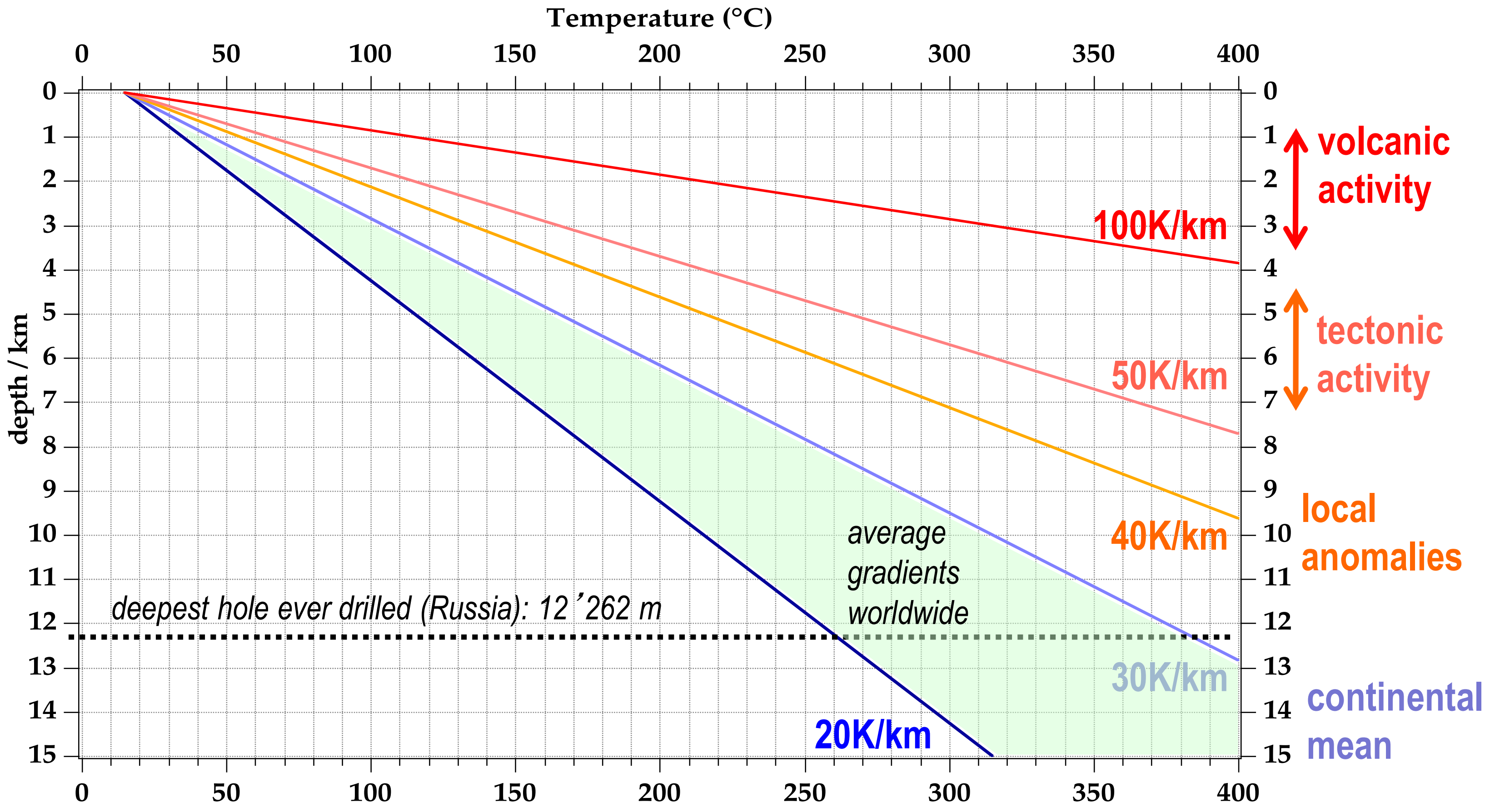
Temperature gradient in the Earth's crust (K / km)



Local heat flux:

1-3 W/m^2

0.1 W/m^2

0.07 W/m^2

0.05 W/m^2

➔ *the __sustainable__ intrinsic geothermal heat flux is very low !*

Geothermal potential (world)

- The average geothermal heat flux is approximately **50 – 60 mW/m²**, from 2 factors:

  1. the flux from the hot Earth interior
     (= residual heat from the Earth's origin; tidal friction)
  2. in the crust (0 to 50 km), radioactive decay (^{40}K, U, Th)

  For illustration: the range over the whole USA subcontinent is 25–150 mW/m²

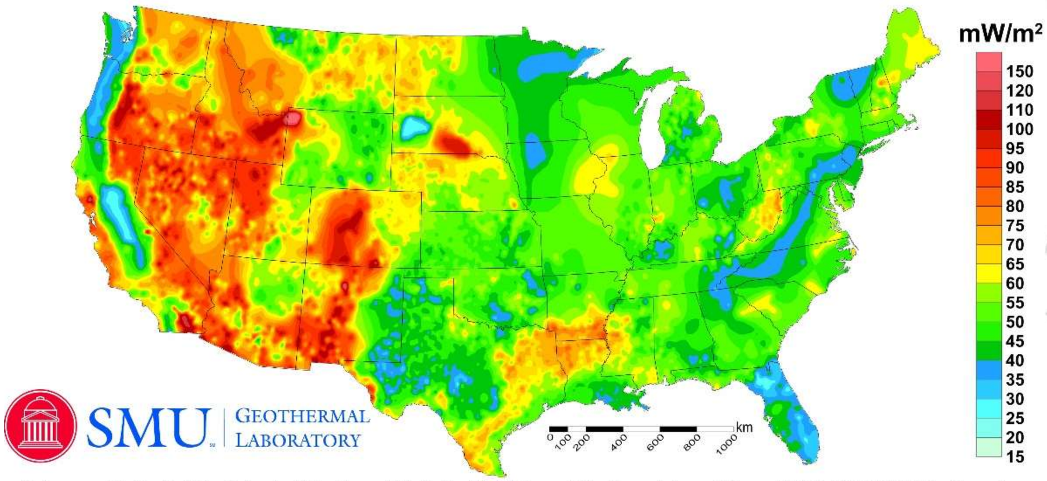
- Worldwide: 50 mW/m²
  → multiplied with the area of the 5 continents (135 Mkm²) => 6.75 $TW_{\underline{heat}}$
  Assuming 20% electrical efficiency and 8000 h load:
  => 1.35 TW_{el} and 11'000 TWh_{el}
  = 50% of current world electrical production
  (exploiting *every square meter* of land on the planet!)

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

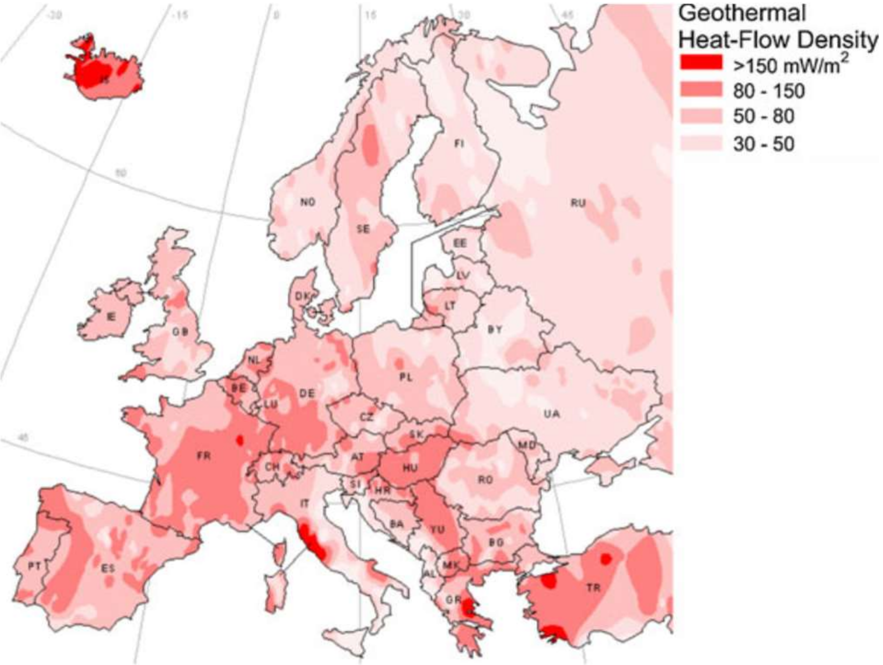
Geothermal heat flux

- USA / Europe

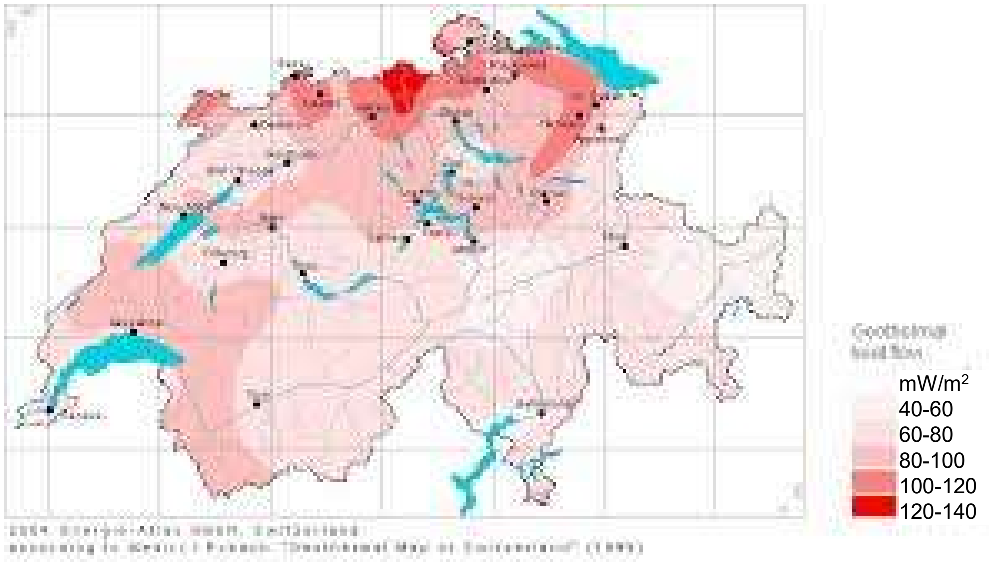
SMU Geothermal Laboratory Heat Flow Map of the Conterminous United States, 2011



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

- assuming 20% electrical efficiency and 8000 h/yr load, this could 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 ca. 25 GW_{el} installed power, or to the yearly present heating needs of ca. 430 PJ

- taking 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} per 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 not in sustainable fashion**

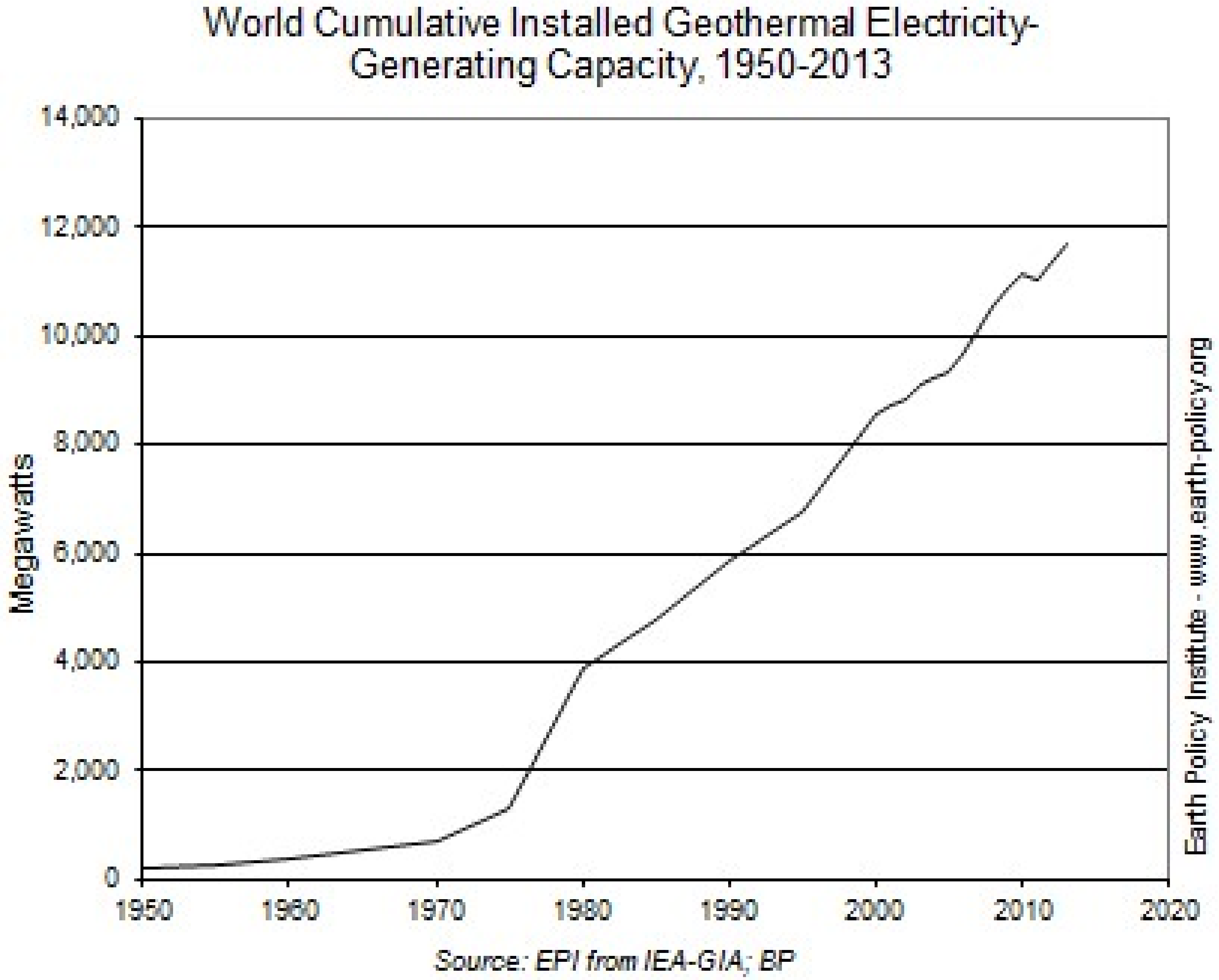
Geothermal reality

- 11 GW_{el} and 16 $GW_{thermal}$ supplied worldwide
- Indonesia could install up to 12 GW_{el}, Japan up to 80 GW_{el}
- Iceland gets 30% of its electricity (580 MW_{el}) and 87% of its heat from geosources, but has only 300⌝000 inhabitants
- The USA is number 1 and has 3 GW_{el} installed geopower, which produces 15 TWh_{el}, but this is only 0.3% of the USA electricity
- Countries around the Pacific ⌞Ring of Fire⌝ can provide a significant share of their needs from geo-energy

Country	Power GW	% of elec.
USA	3.1	0.3
Philippines	**1.9**	**27**
Indonesia	1.2	3.7
Mexico	1	3
Italy	0.84	1.5
NZ	**0.63**	**10**
Iceland	**0.58**	**30**
Japan	0.54	0.1
El Salvador	**0.2**	**25**
Kenya	**0.17**	**11**
Costa Rica	**0.17**	**14**
Nicaragua	**0.1**	**10**
World	11	0.3

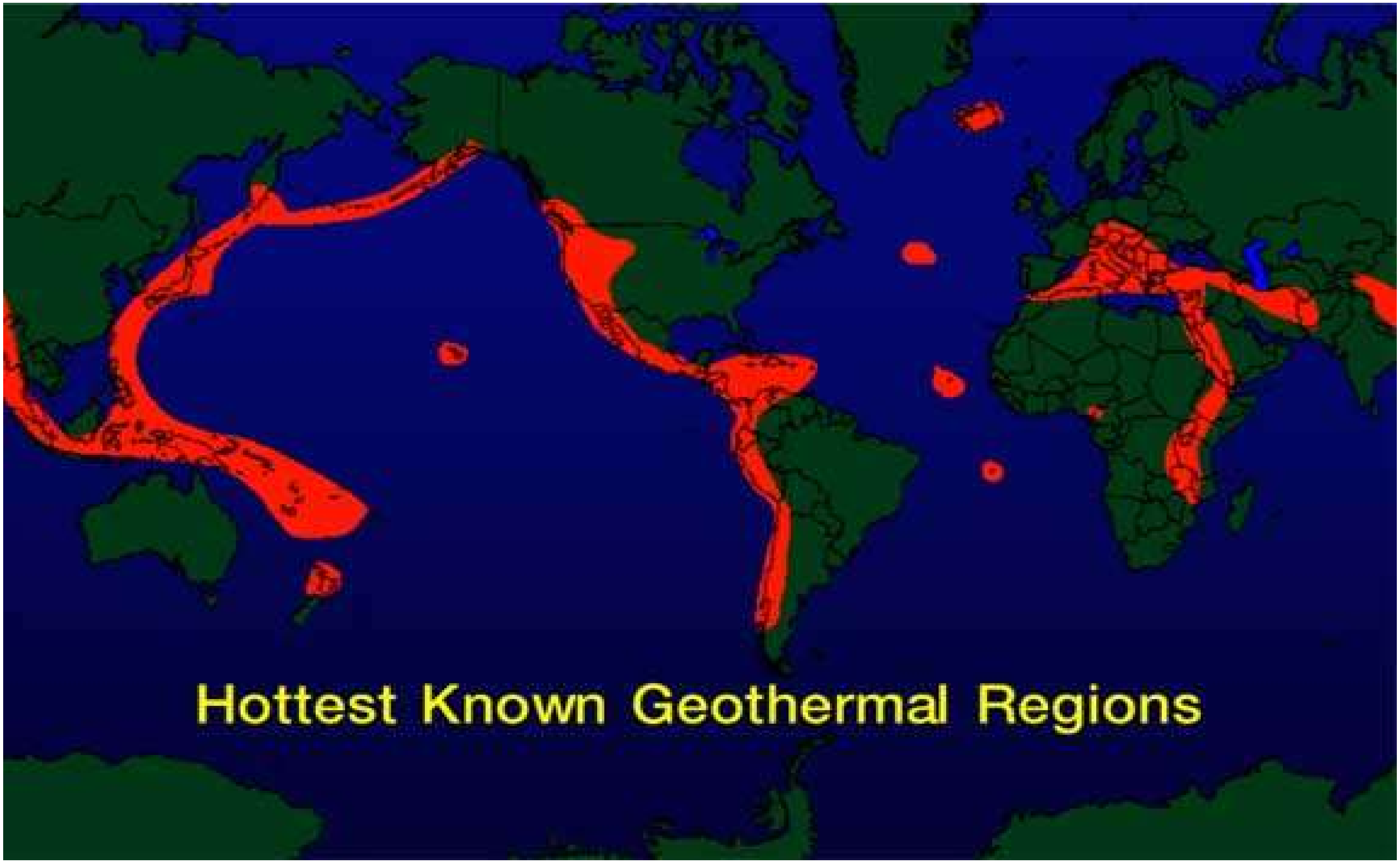
> 60 TWhe

Geothermal reality

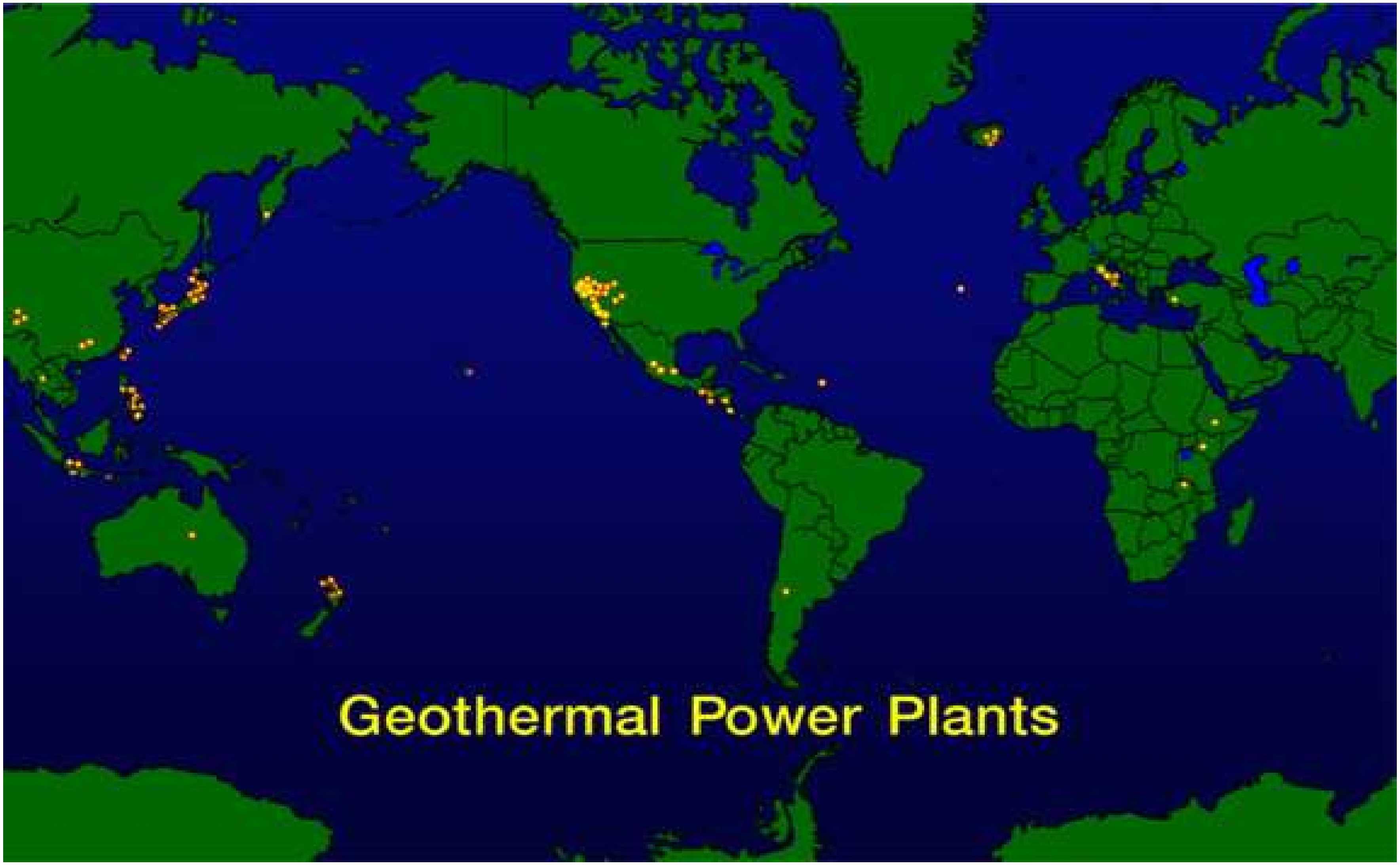


Source: EPI from IEA-GIA; BP

Occurrence – Locations – the ˻Ring of Fire˺



Distribution of geothermal plants



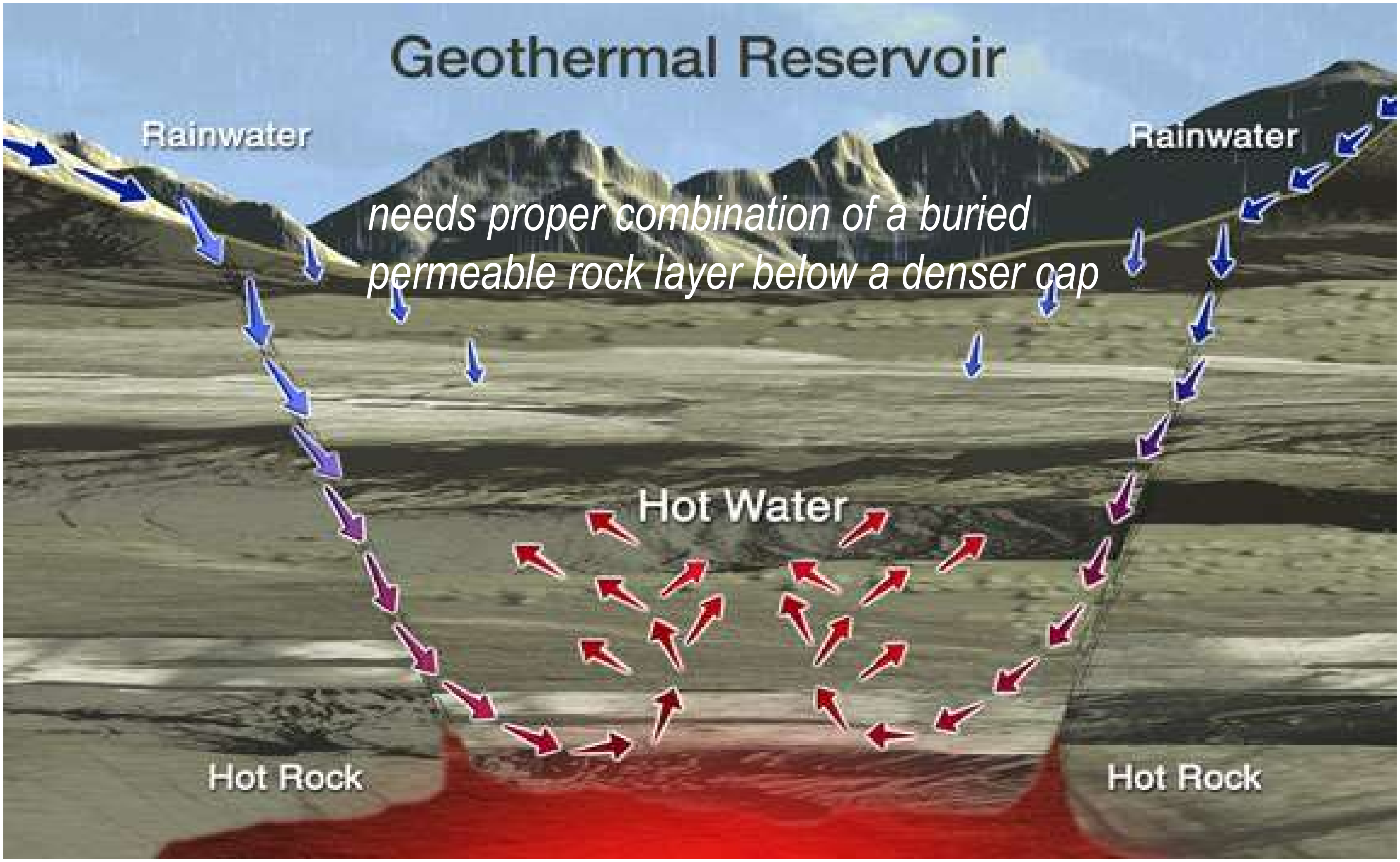
Italy (Tuscany) as pioneer

- 1^{st} plant worldwide,1911, in Larderello
  - 200°C at 1 km depth; max 437°C at 3.2 km
  - 1 W/m^2 heat flux; ca. 200 km^2 active area
  - 160-250°C, superheated steam 4-20 bar
  - avgerage flux 25 t/h (7 kg/s), max 350 t/h
  - **790 MW$_{el}$, >5.5 TWh$_{el}$; 10% of world's geopower**

Some general features of geothermal power

- **unsustainable** !
  - heat extraction rate >> geothermal heat flux => the soil is cooled down (v.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
  - f.ex. 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 ⌞fuel⌝) is very high!

Hydrothermal reservoirs



needs proper combination of a buried permeable rock layer below a denser cap

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**

Classification of hydrothermal reservoirs

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

Different forms

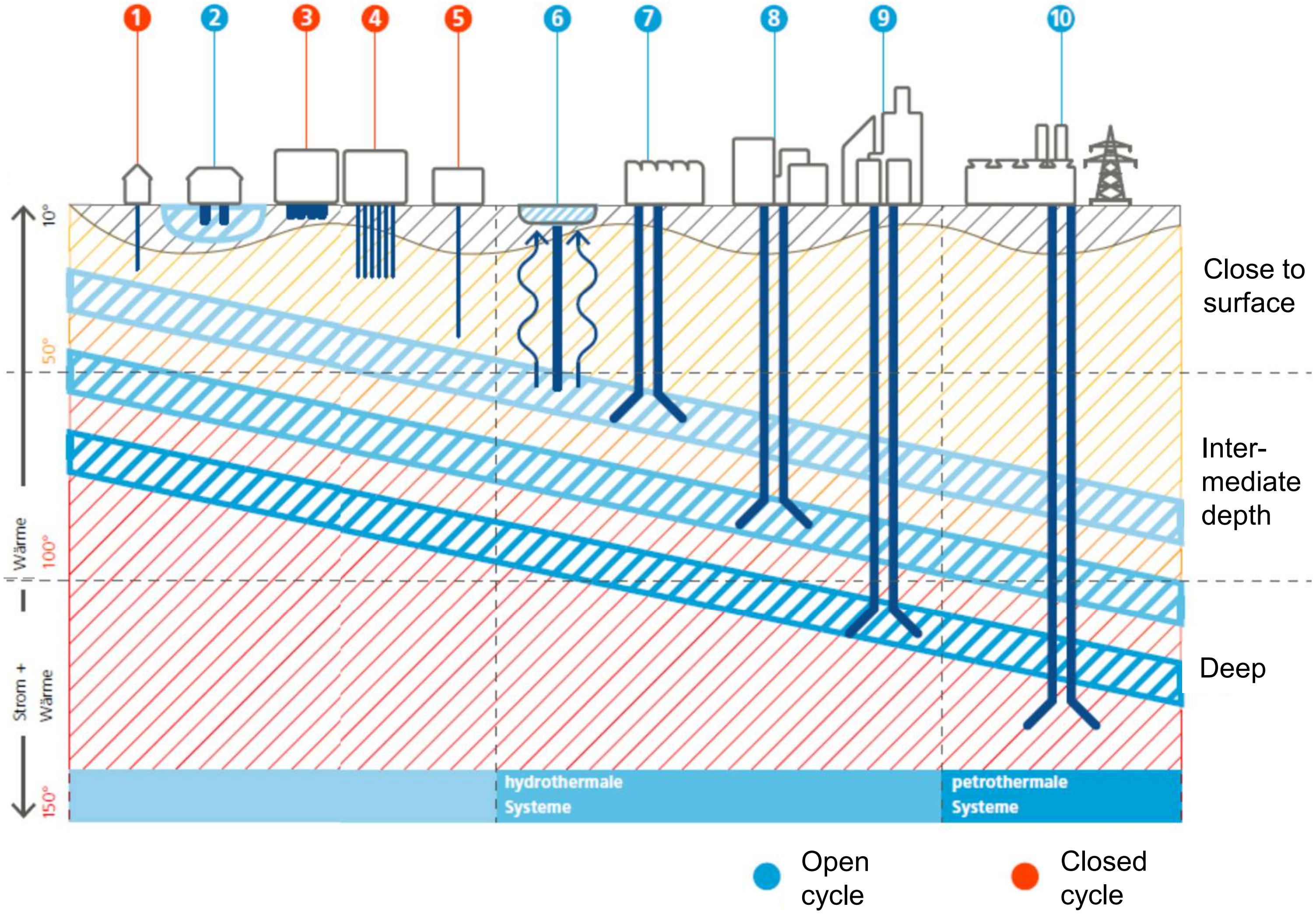
- ① Earth heat probe
- ② Groundwater use
- ③ Geo-structures
- ④ Earth heat probe, field
- ⑤ Deep earth heat probe

- ⑥ Thermal bath

Hydrothermal, intermed. depth:
- ⑦ Heat for industry, agriculture
- ⑧ Heat for heating and hot water

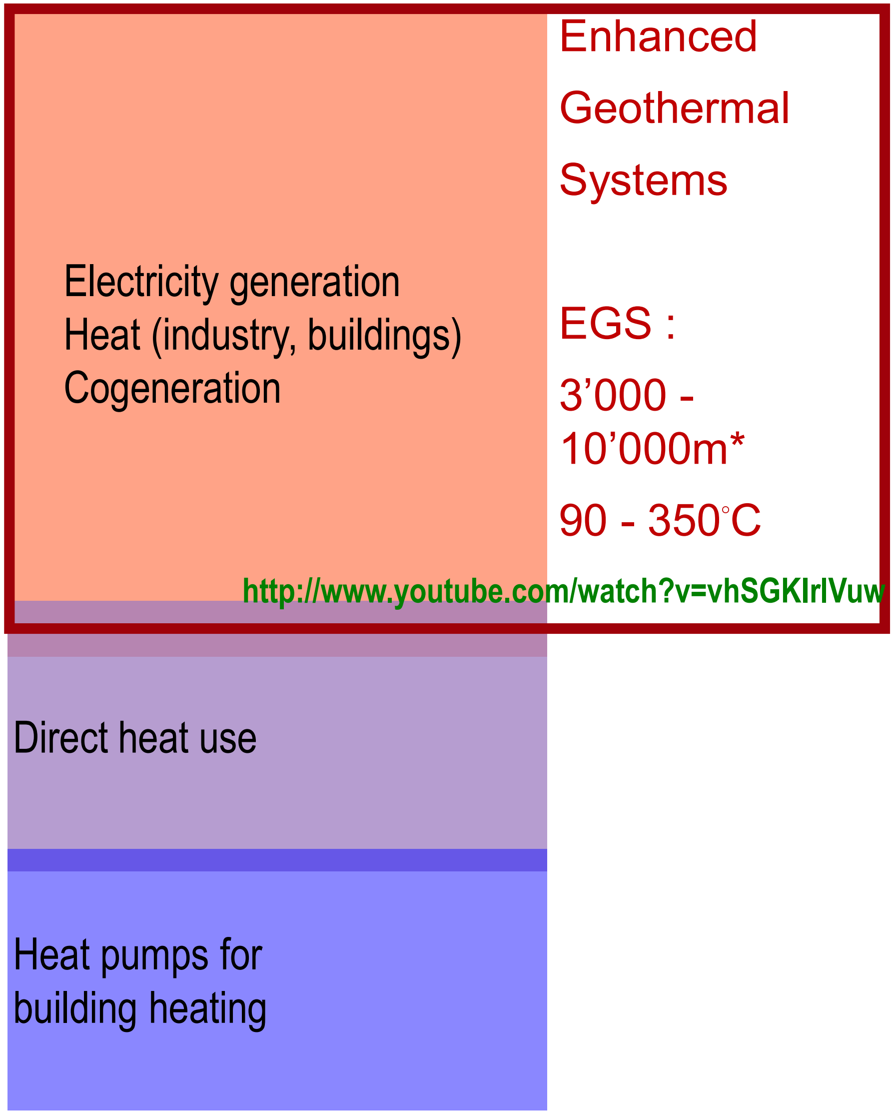
Hydrothermal, deep:
- ⑨ Heat and power

Petrothermal:
- ⑩ Heat and power



Energie Schweiz: Geothermie in der Schweiz, 2006

Temperature level usage



Enhanced Geothermal Systems

EGS :

3’000 - 10’000m*

90 - 350°C

Electricity generation
Heat (industry, buildings)
Cogeneration

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

Direct heat use

Heat pumps for building heating

•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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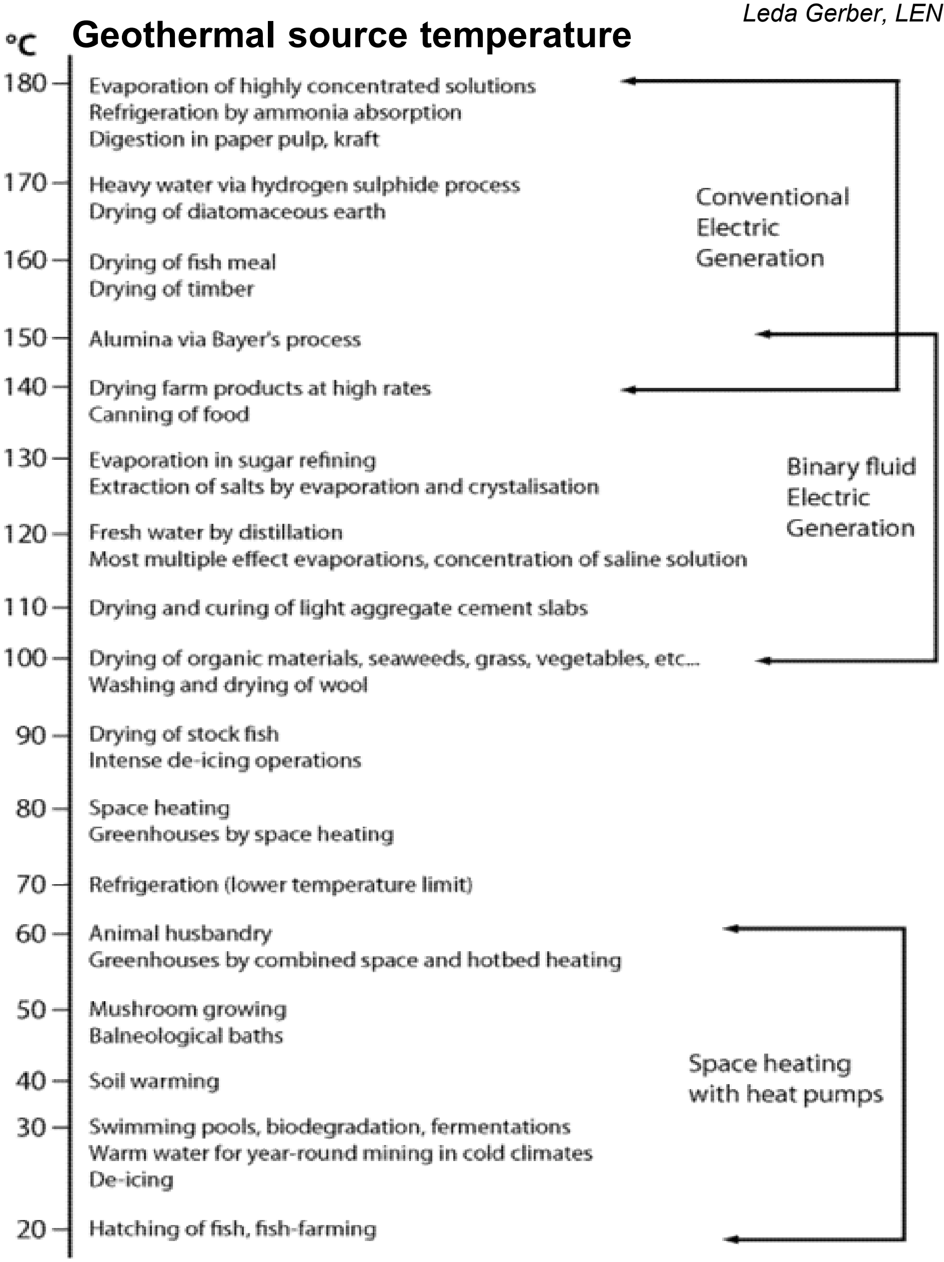


Geothermal source temperature

°C	
180	Evaporation of highly concentrated solutions Refrigeration by ammonia absorption Digestion in paper pulp, kraft
170	Heavy water via hydrogen sulphide process Drying of diatomaceous earth
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 crystalisation
120	Fresh water by distillation Most multiple effect evaporations, concentration of saline solution
110	Drying and curing of light aggregate cement slabs
100	Drying of organic materials, seaweeds, grass, vegetables, etc... Washing and drying of wool
90	Drying of stock fish Intense de-icing operations
80	Space heating Greenhouses by space heating
70	Refrigeration (lower temperature limit)
60	Animal husbandry Greenhouses by combined space and hotbed heating
50	Mushroom growing Balneological baths
40	Soil warming
30	Swimming pools, biodegradation, fermentations Warm water for year-round mining in cold climates De-icing
20	Hatching of fish, fish-farming

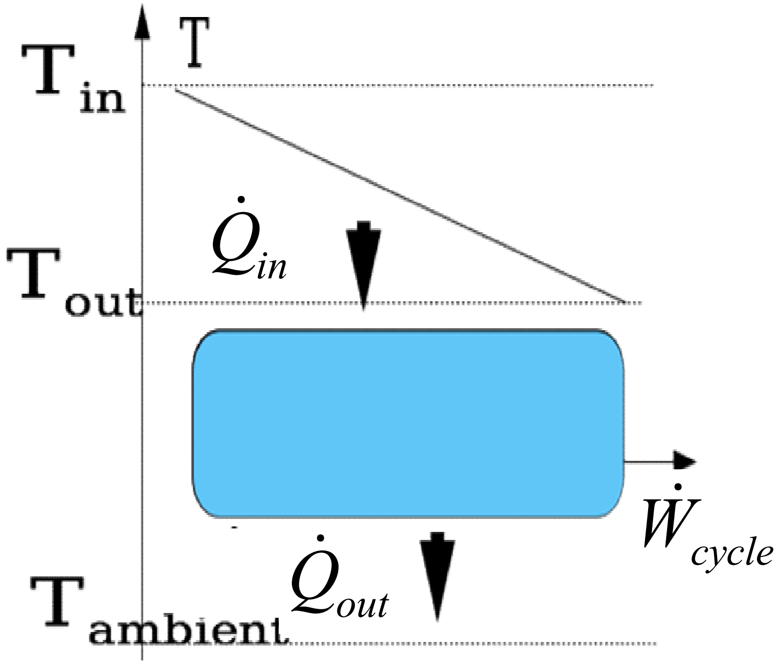
Electricity production potential

Thermodynamics :

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

Maximum available power (exergy):

$$\dot{E}x = \underbrace{\left(1-\frac{T_0}{T_h}\right)}_{\text{Carnot factor}}\dot{Q}_{in}$$



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

*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 $T_{h,in}$ to $T_{h,out}$, and a cold fluid, warming from $T_{c,in}$ to $T_{c,out}$, 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:

$$Q = U \cdot A \cdot LMTD$$

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

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

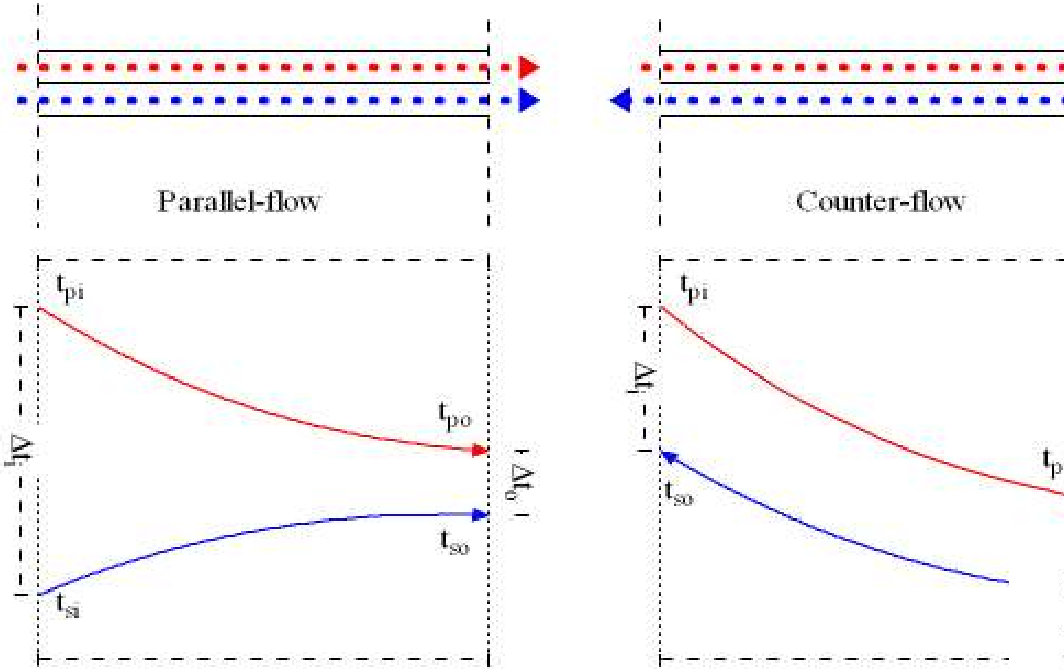
  heat is extracted at $T_{h,in}$ and reinjected at $T_{h,out}$;

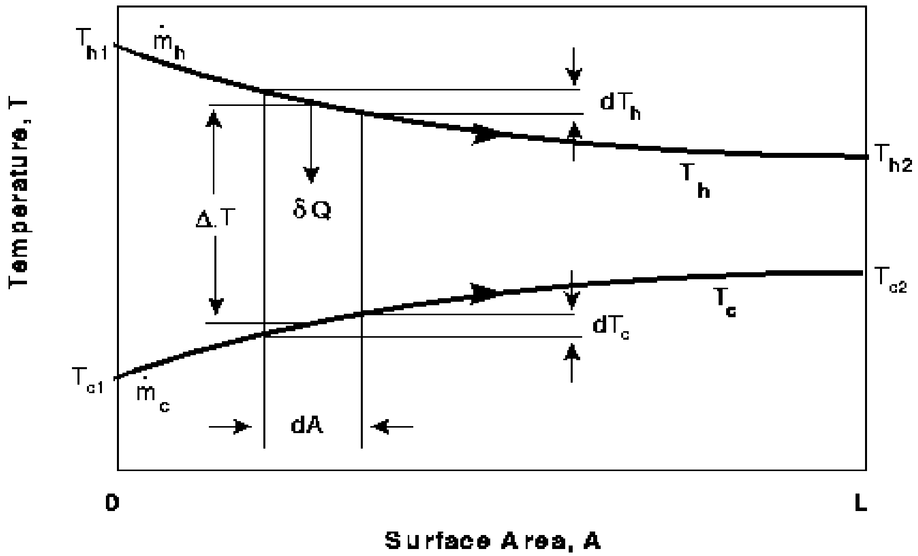
  the *average hot source temperature T_h*

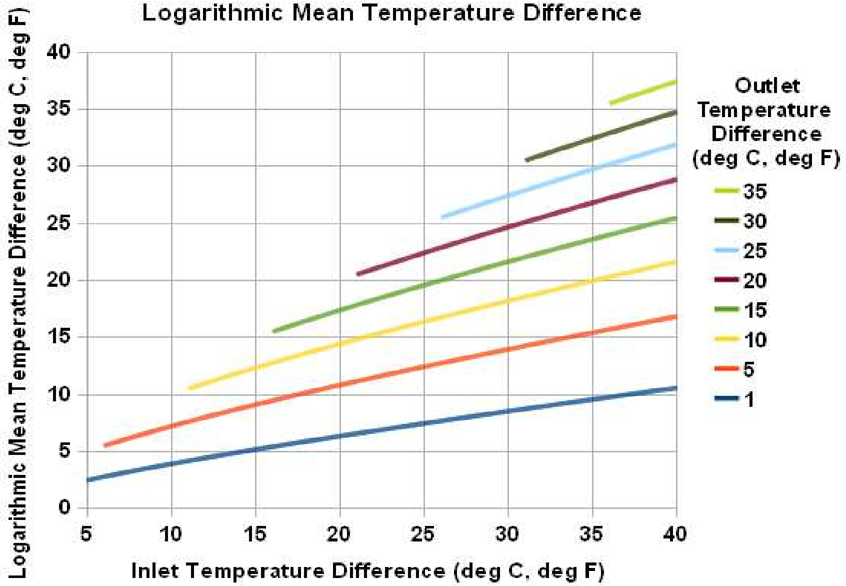
  is then determined from its logarithmic mean :

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

˪ logarithmic mean temperature







The Engineering ToolBox

www.EngineeringToolBox.com

Electricity production: energy vs exergy efficiency

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

Pilot project for electricity from EGS exploitation at 5000m

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

(LMT_h=120° C)

(take T_a as 15° C)

$\Rightarrow$ Heat flux Q = massflow * Cp " ΔT
= 35 (kg/s) * 4184 (kj/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

Importance of T-level

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

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

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

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

$C_p(H_2O)$=4184 J/kg

$$\theta = 1 - \frac{T_a}{\underbrace{\frac{T_{in} - T_{out}}{ln \frac{T_{in}}{T_{out}}}}_{T_h}}$$

0.368

max. electricity: 3864 kWe

0.288

max. electricity: 3024 kWe

- 22 %

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

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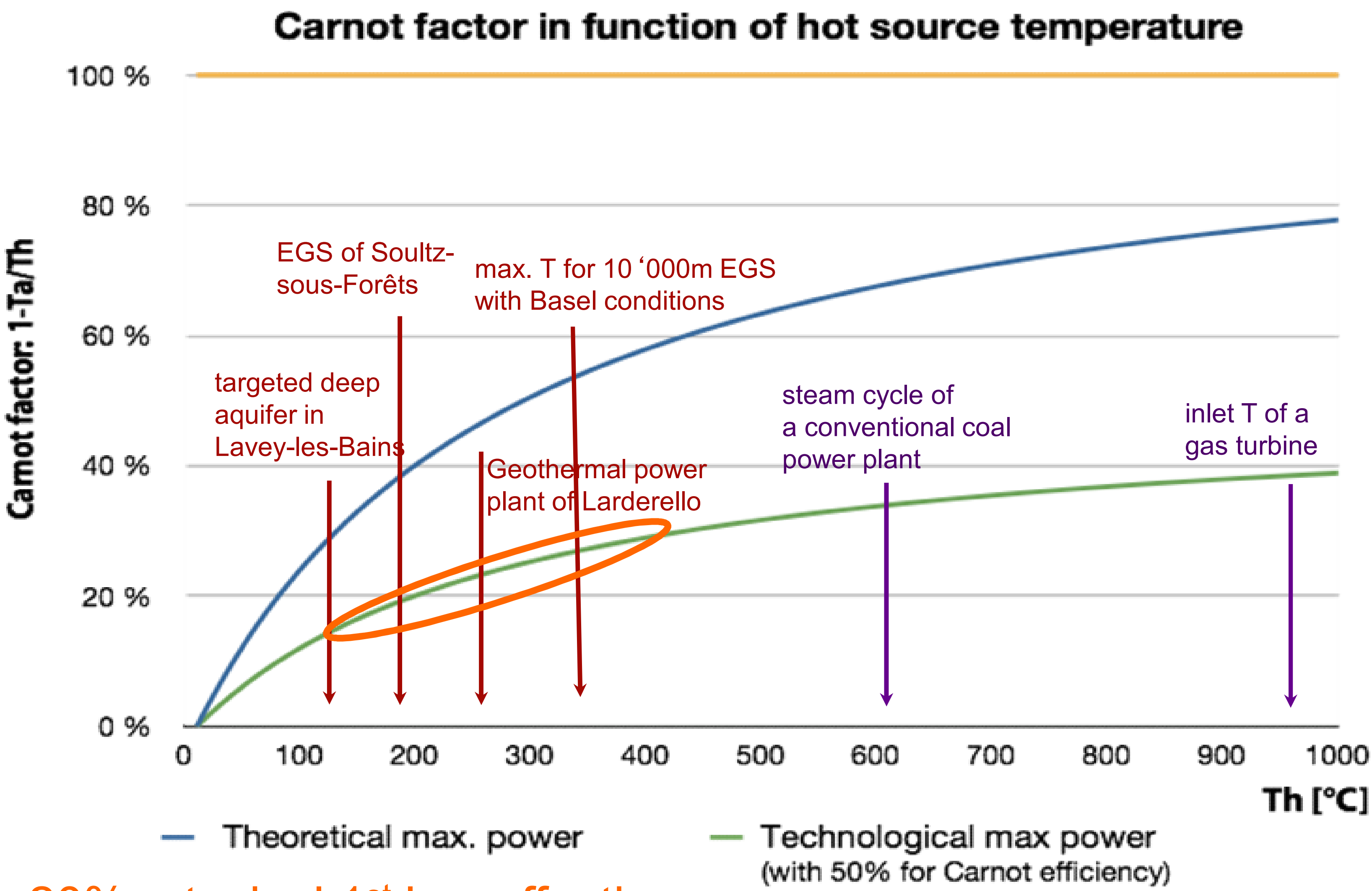
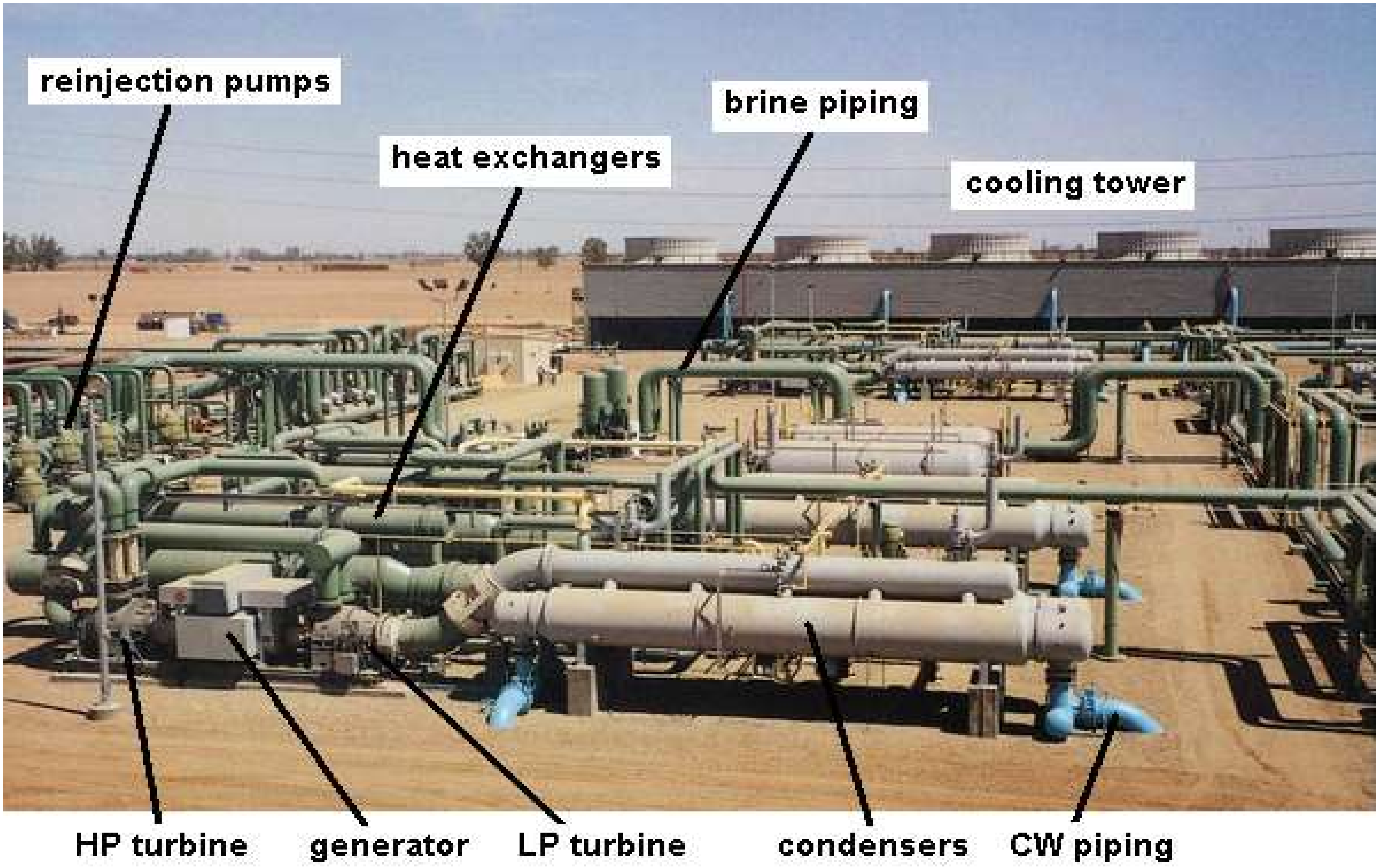


20% = typical 1st law effectiveness

Geothermal plant, aerial view

Ronald DiPippo: Geothermal power plants: Elsevier 2008

Geothermal plant, closer view



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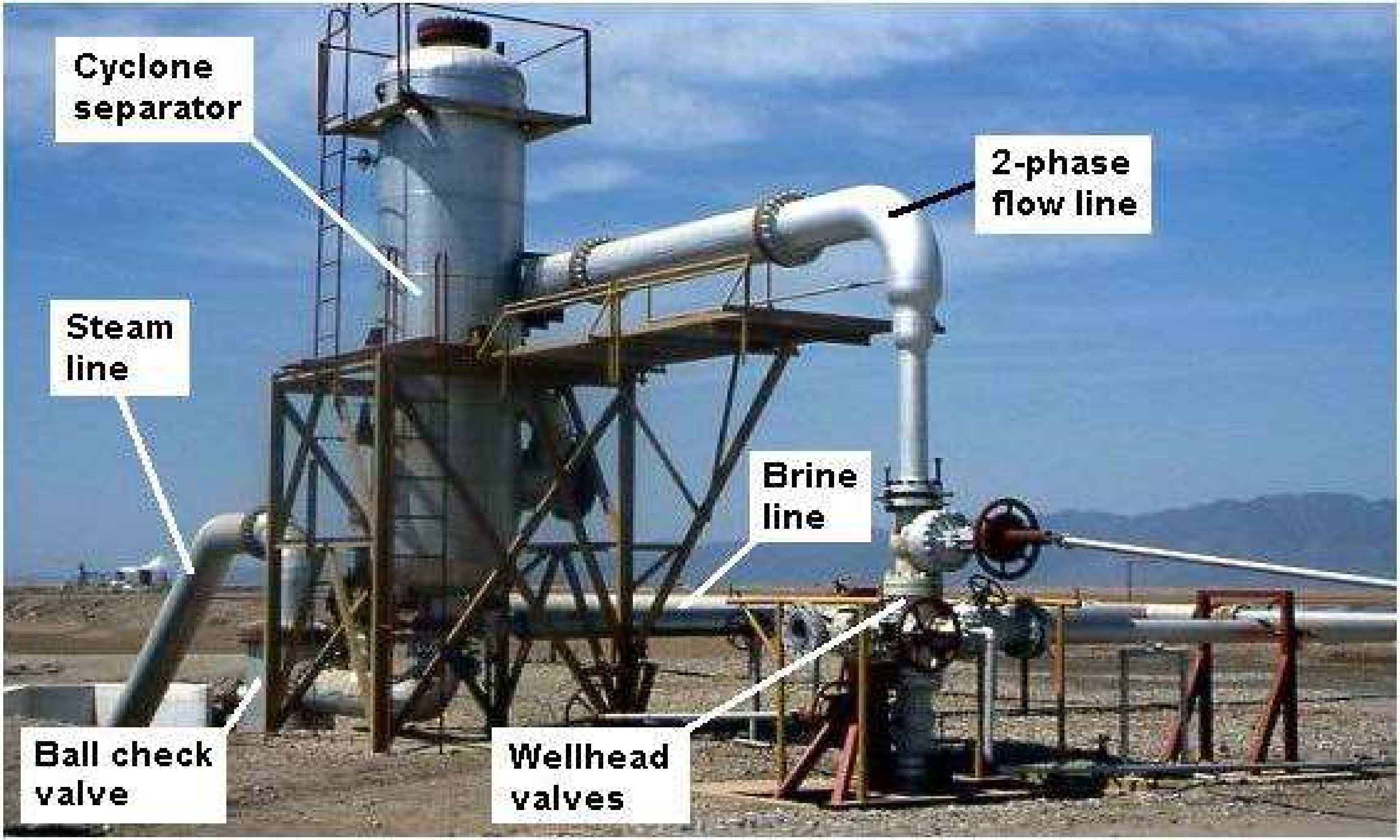
Wellhead view



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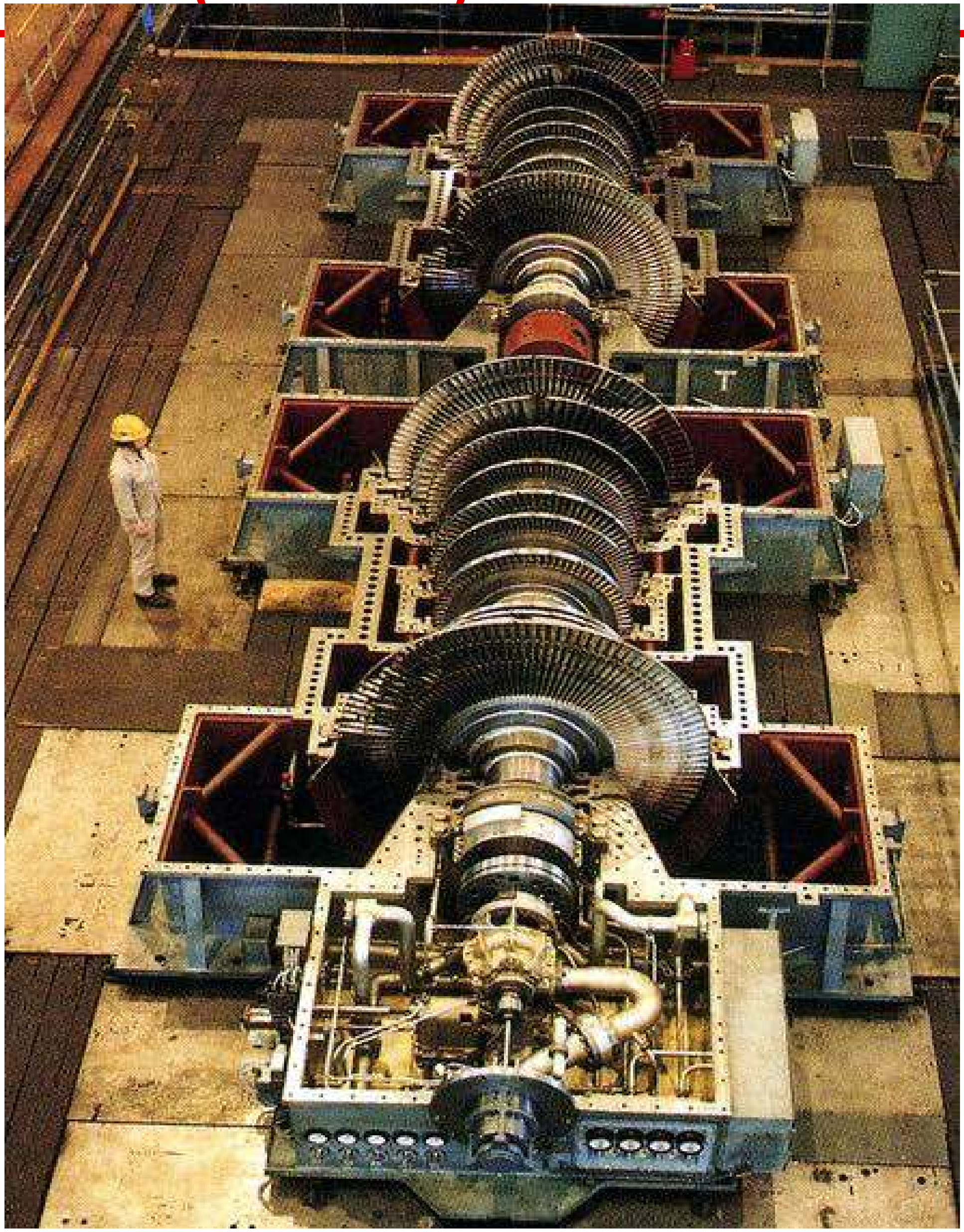
Turbine rotor (110 MW)



Ronald DiPippo: Geothermal power plants: Elsevier 2008

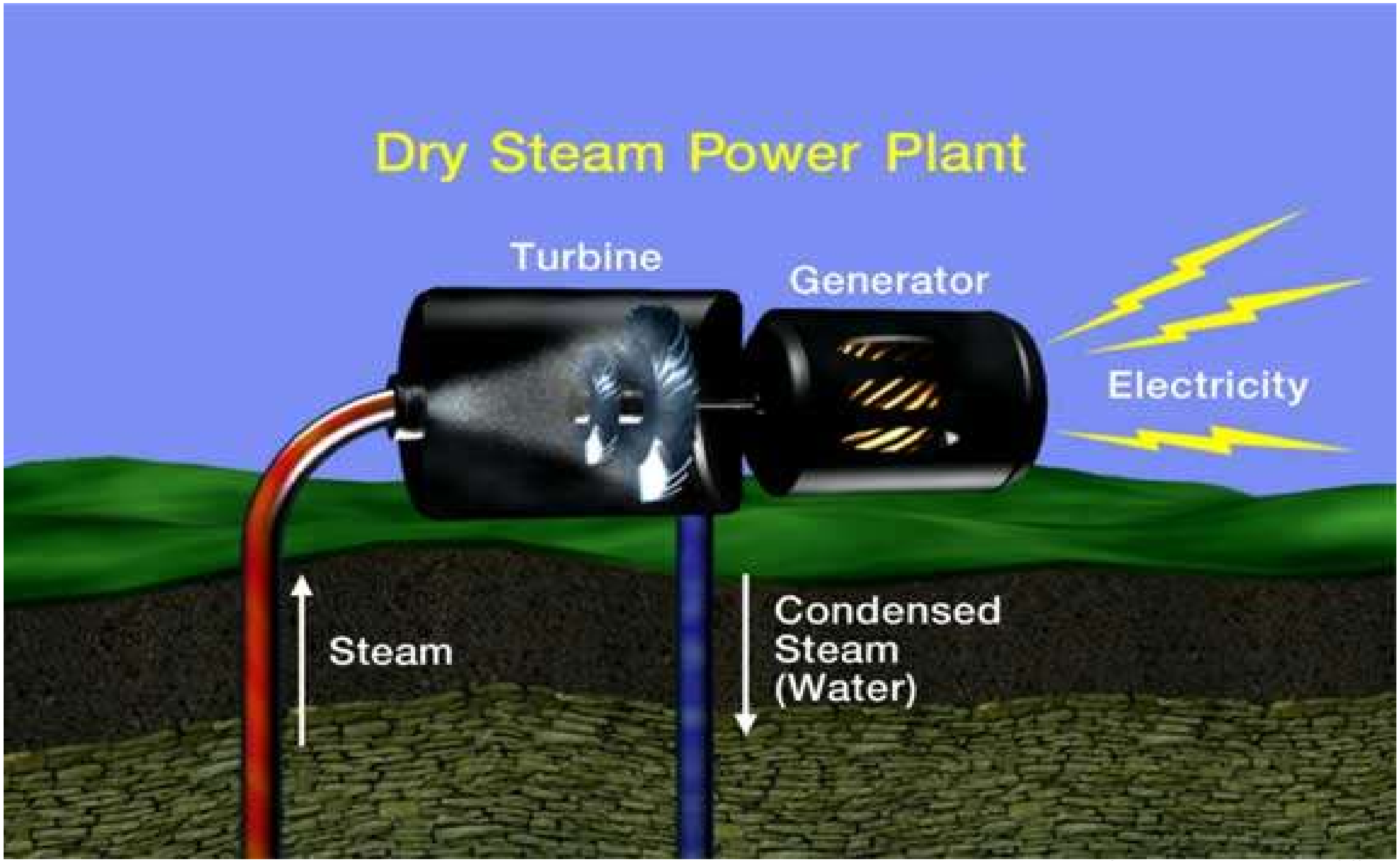
Hatchobaru plant, Japan

Ronald DiPippo: Geothermal power plants: Elsevier 2008

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

Ronald DiPippo: Geothermal power plants: Elsevier 2008

Dry steam power plant



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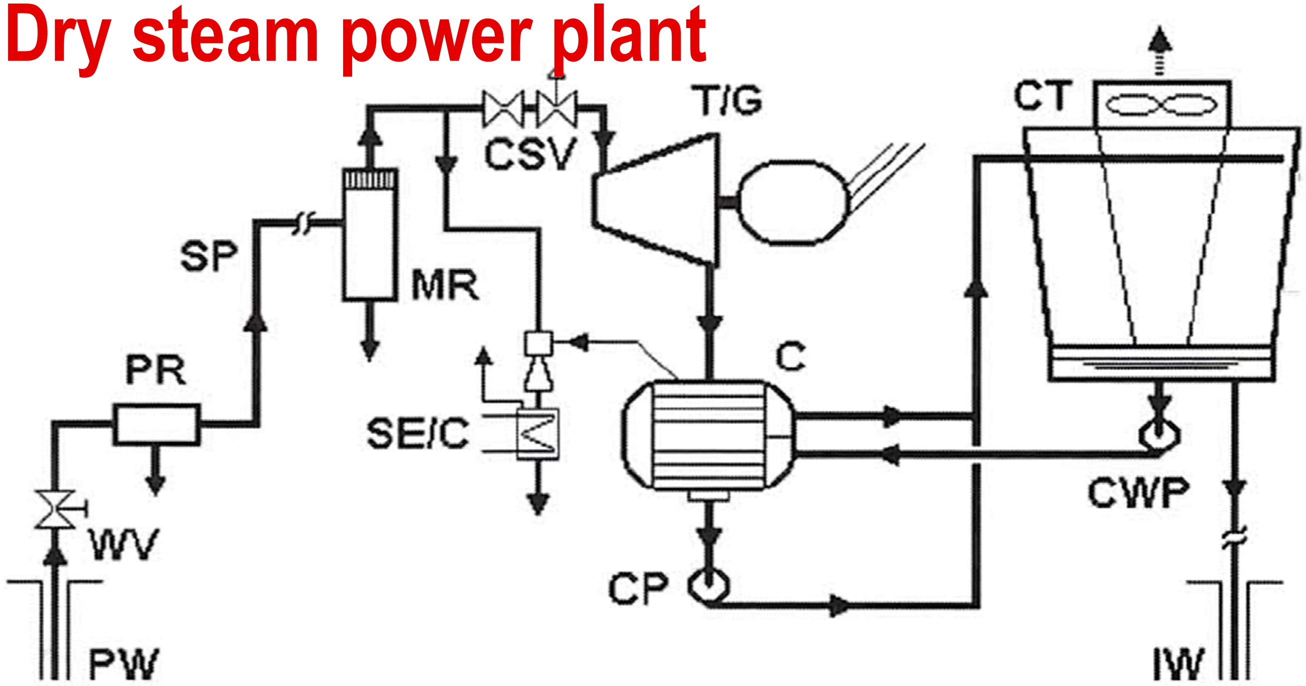
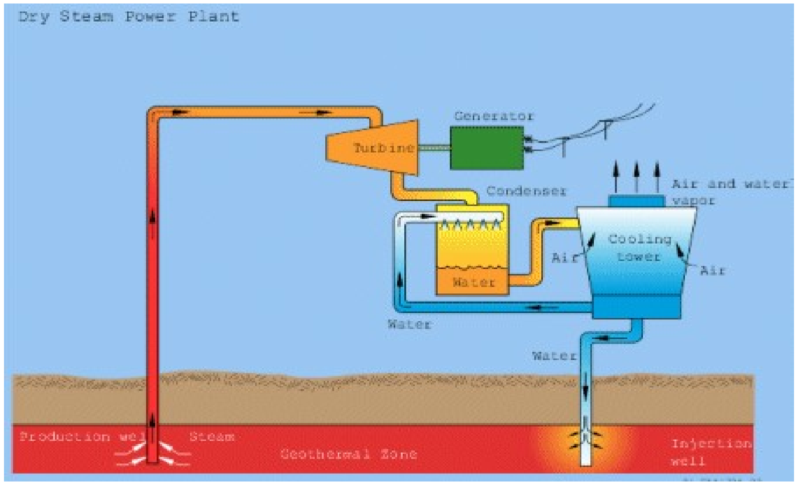
Steam (no water) shoots up the wells directly into a turbine.
Dry steam fields are ***rare***.

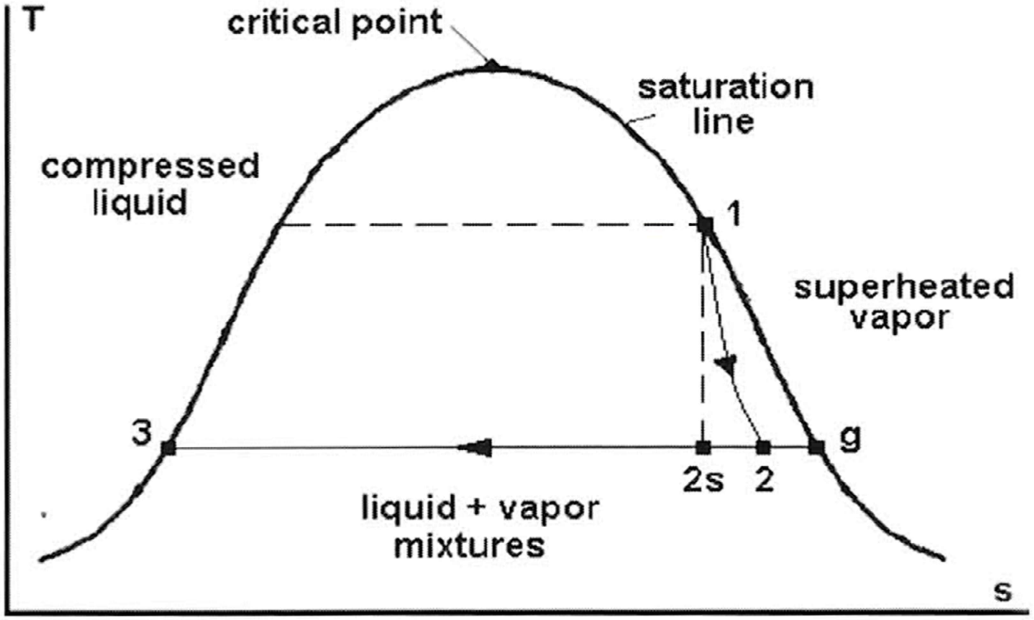
Dry steam power plant

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

Dry steam power plant





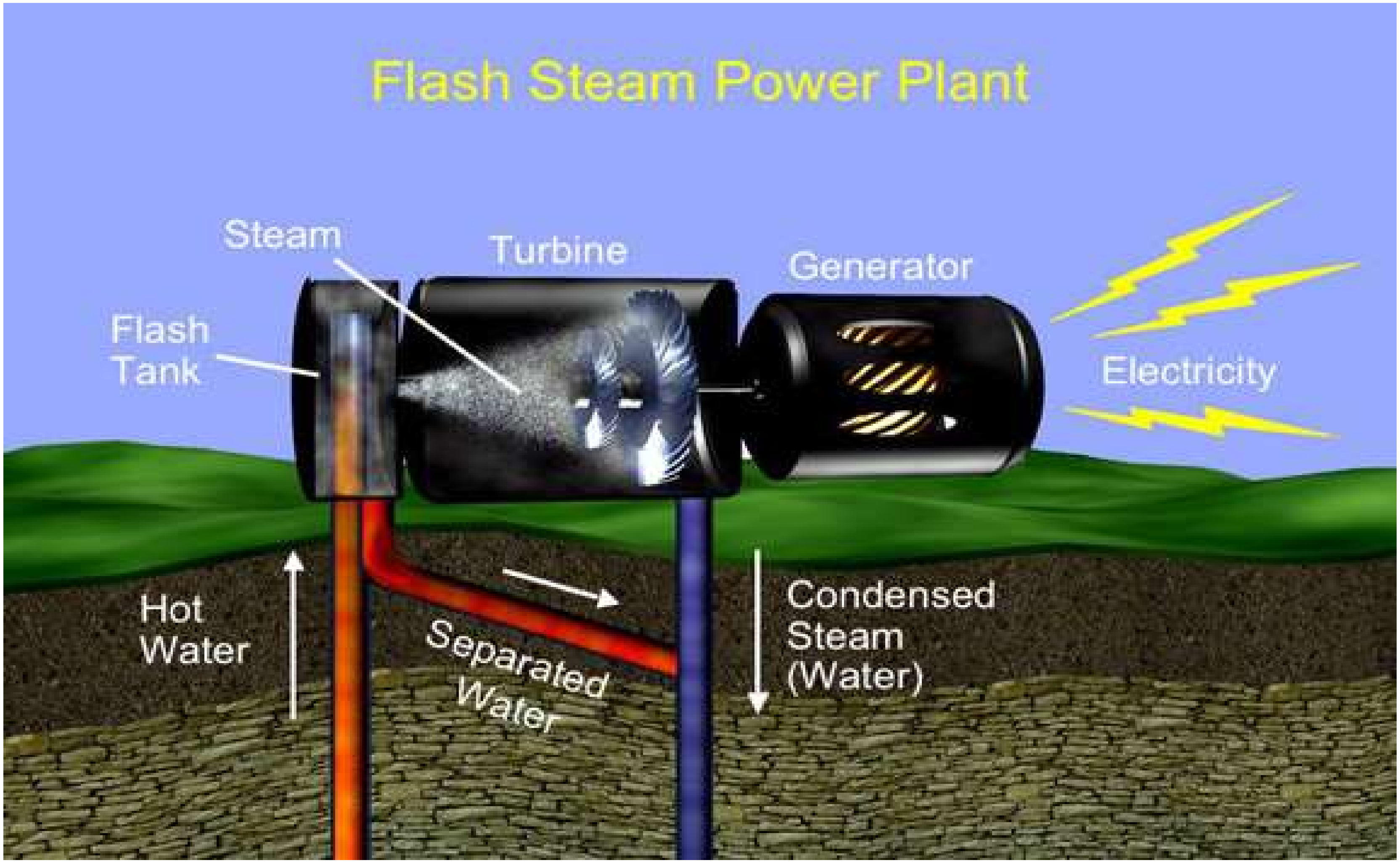


Flash steam plant

East Mesa, California

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

Flash steam power plant



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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

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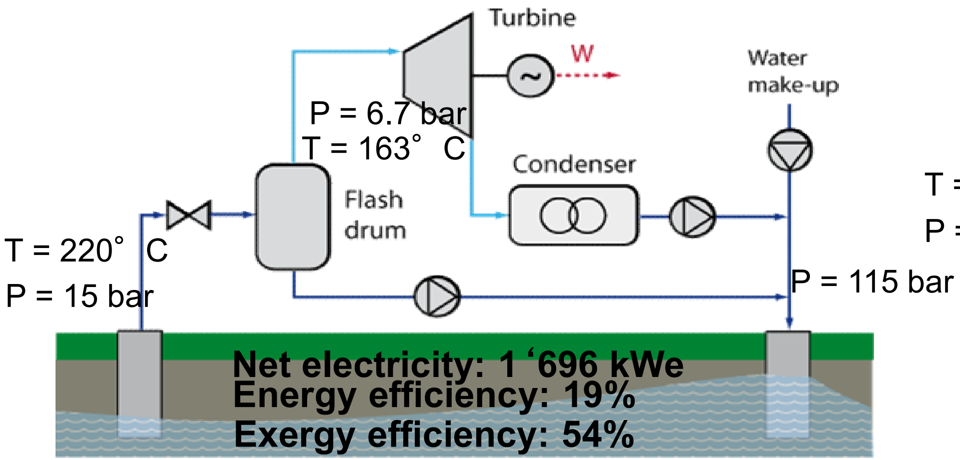
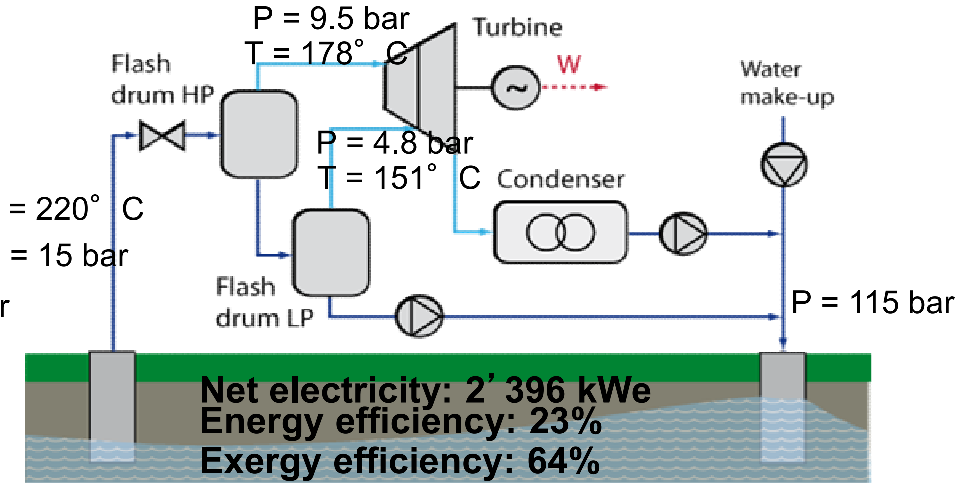
- Direct use of the geofluid (=liquid, or mixture of gas and liquid)
- Separation between liquid and gas (power from steam turbine)
- Temperature lower limit: 150-180°C
- Quality of the geofluid is critical (dissolved minerals!)



Net electricity: 1 ‘696 kWe
Energy efficiency: 19%
Exergy efficiency: 54%

Single-flash system

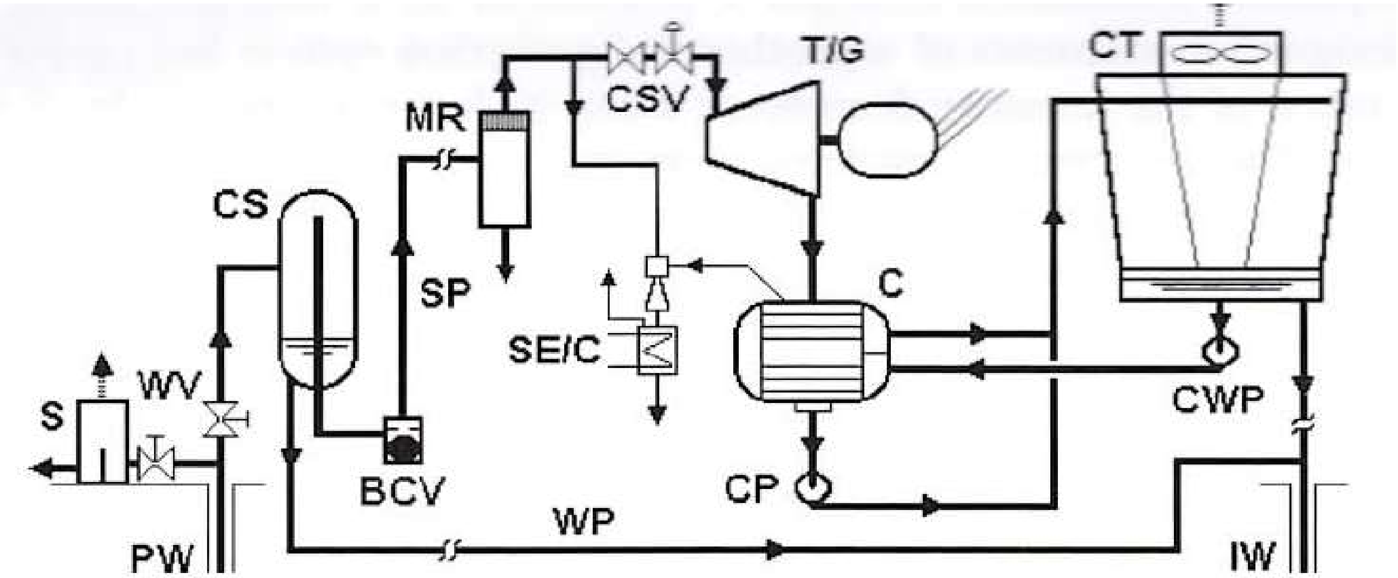
T = 220° C
P = 15 bar

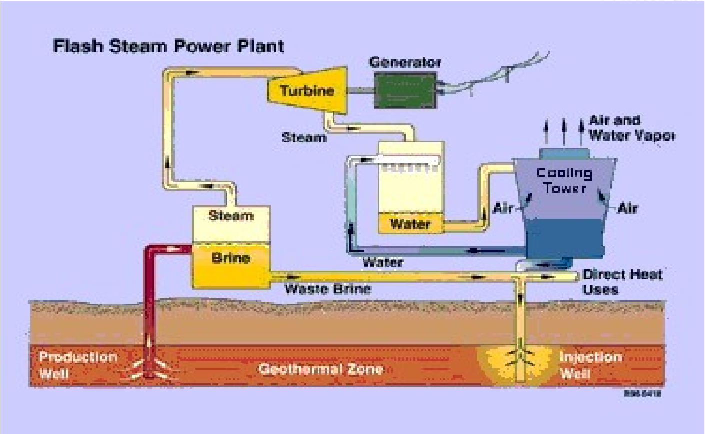


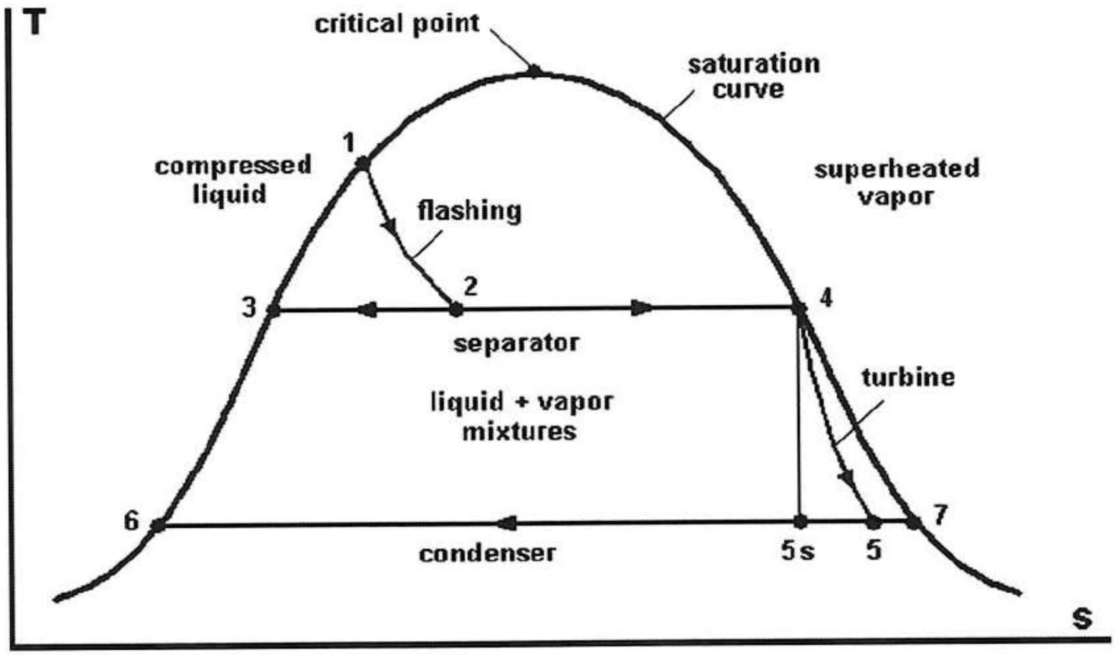
Net electricity: 2’ 396 kWe
Energy efficiency: 23%
Exergy efficiency: 64%

Double-flash system
Additional power generation
More expensive

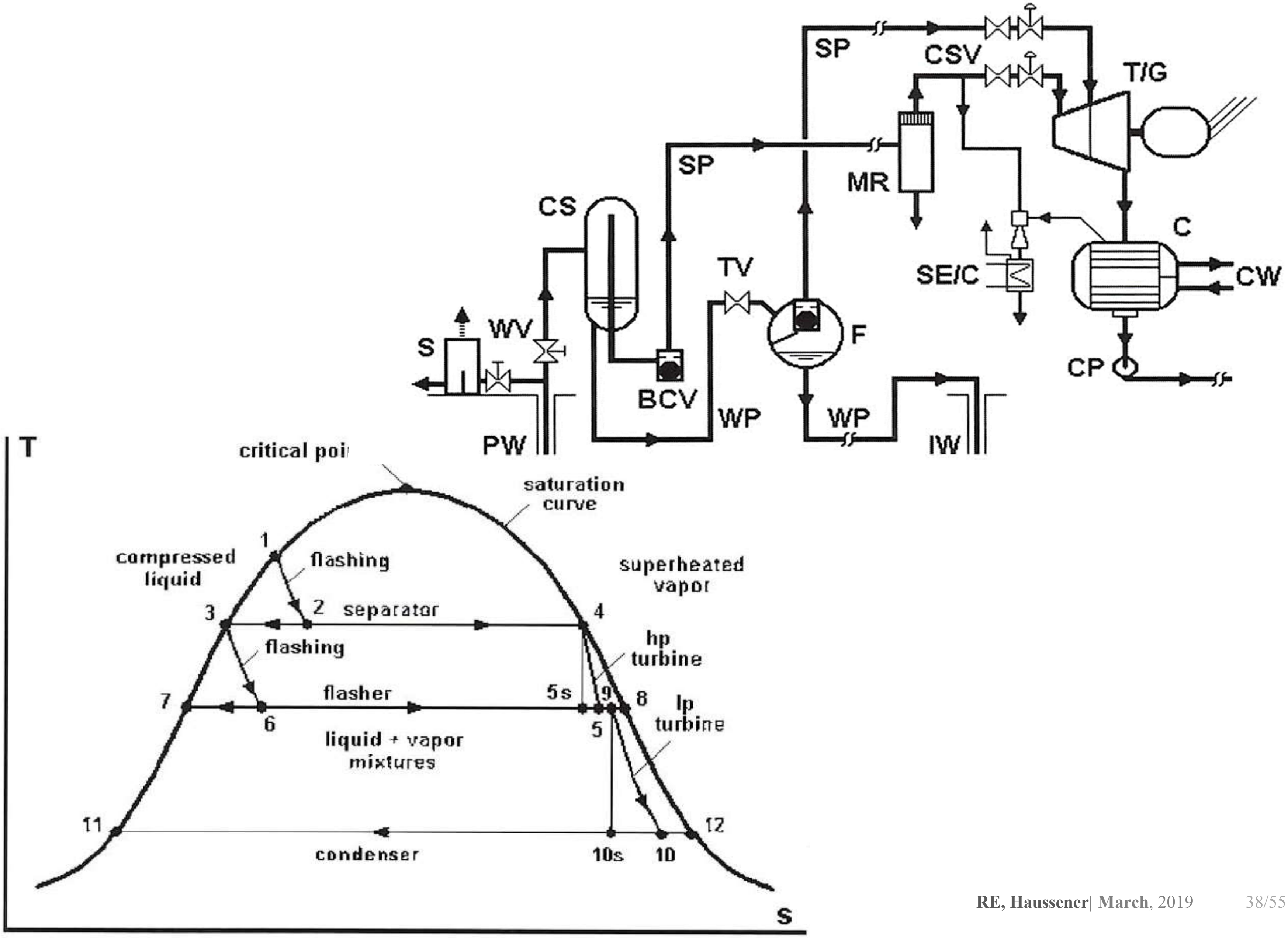
Single-flash schematics



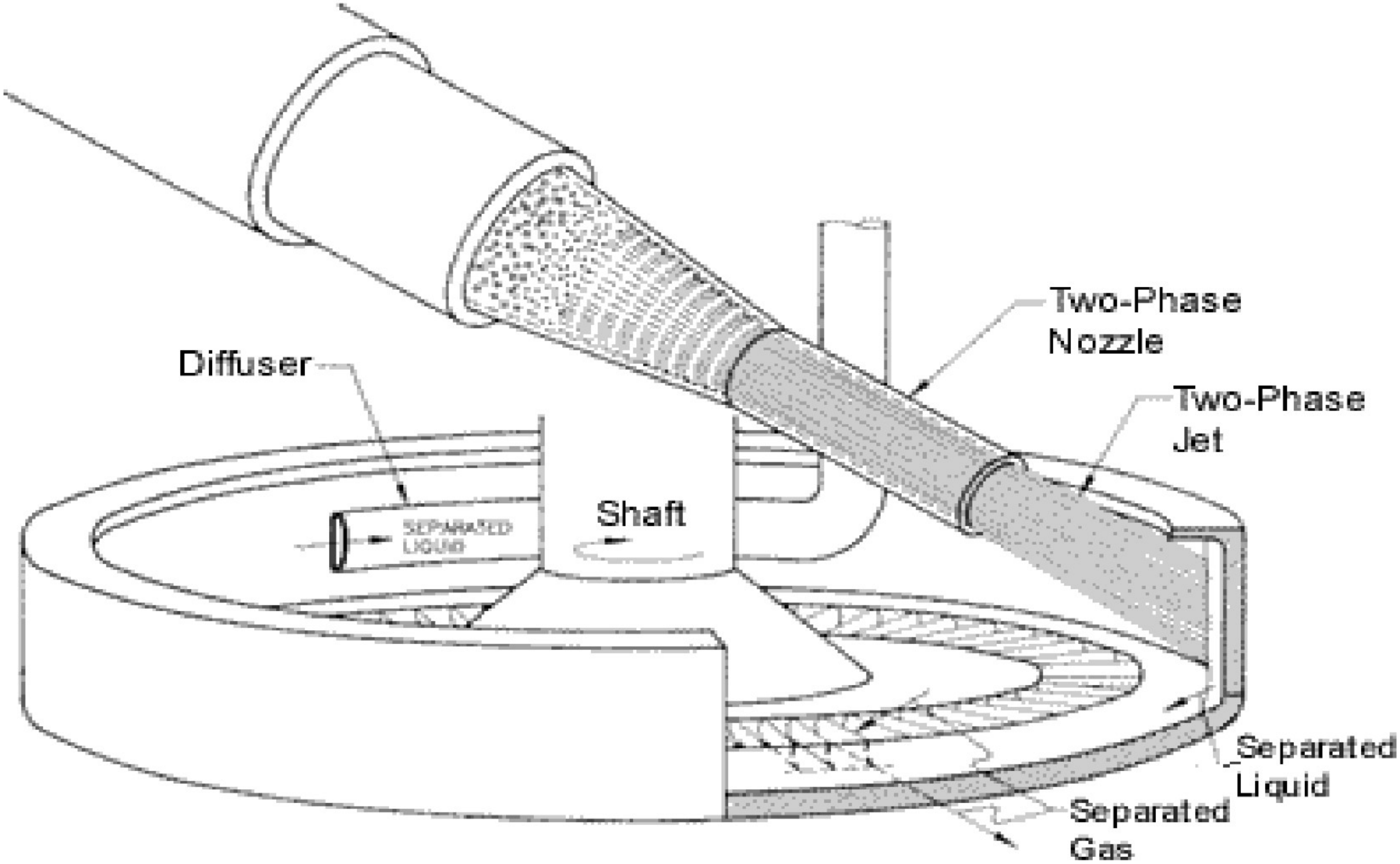




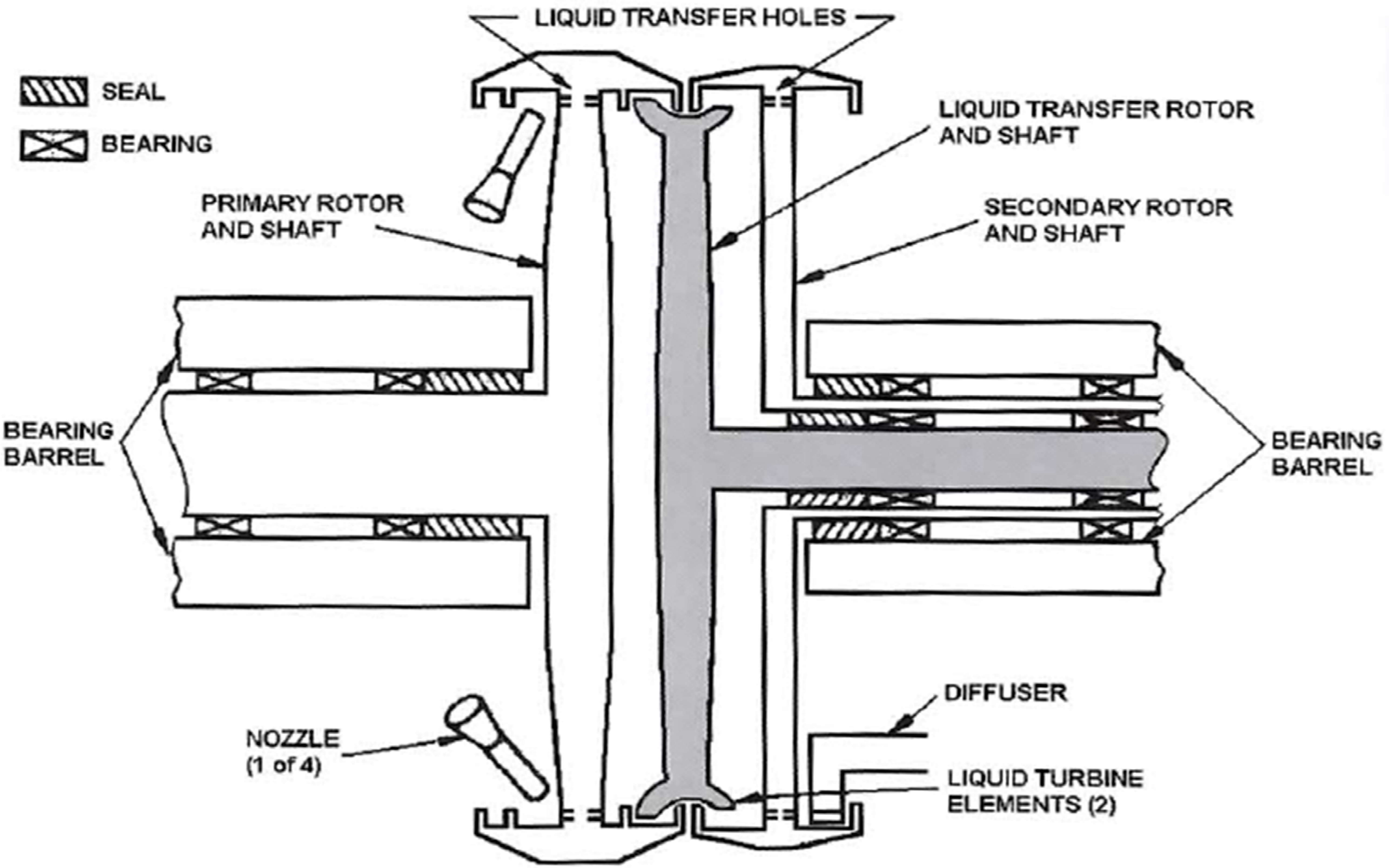
Double-flash schematics



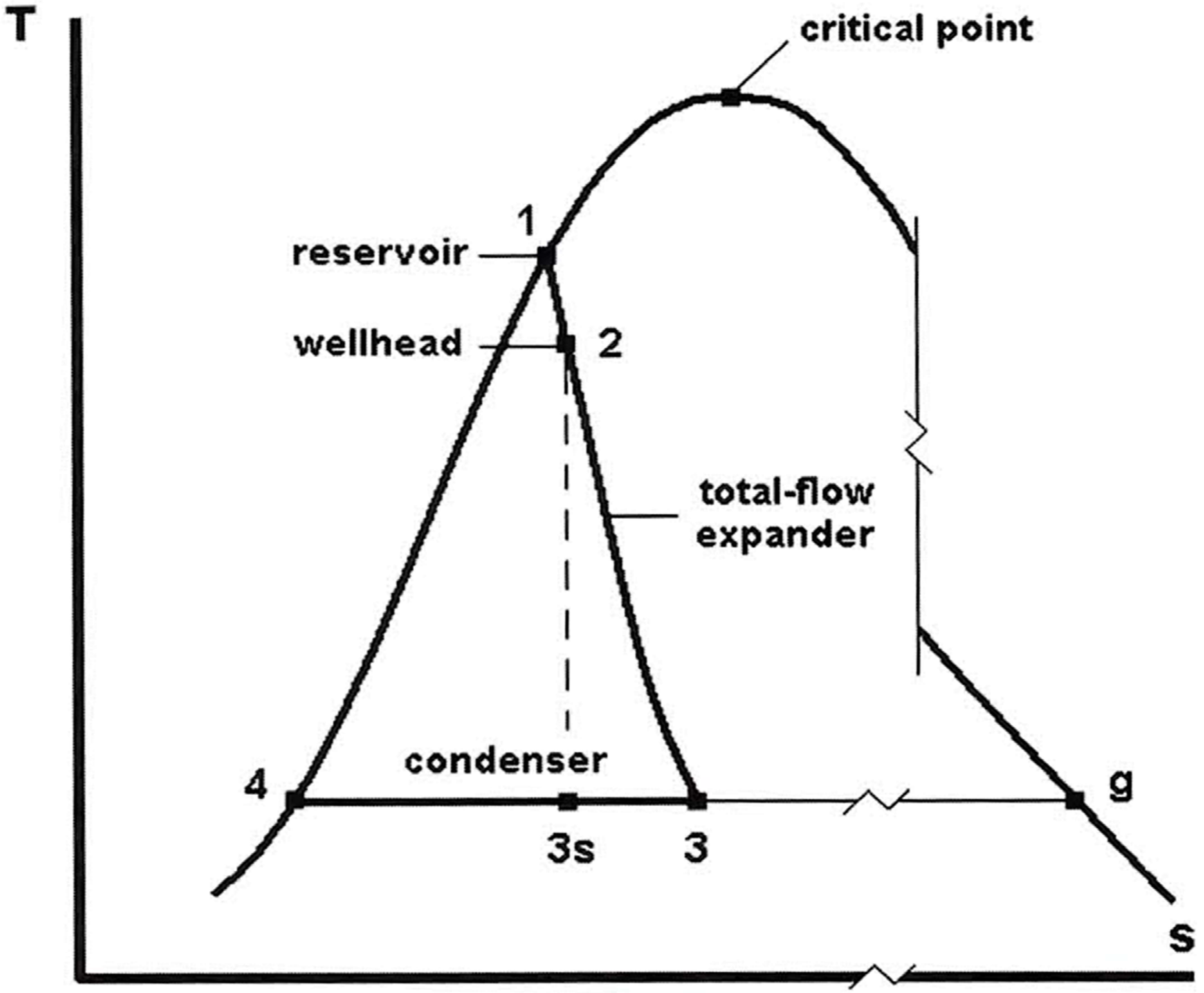
Example of turbine for two-phase expansion



Direct expansion from saturated liquid: biphase (˻total flow˺) turbine



Total flow expander

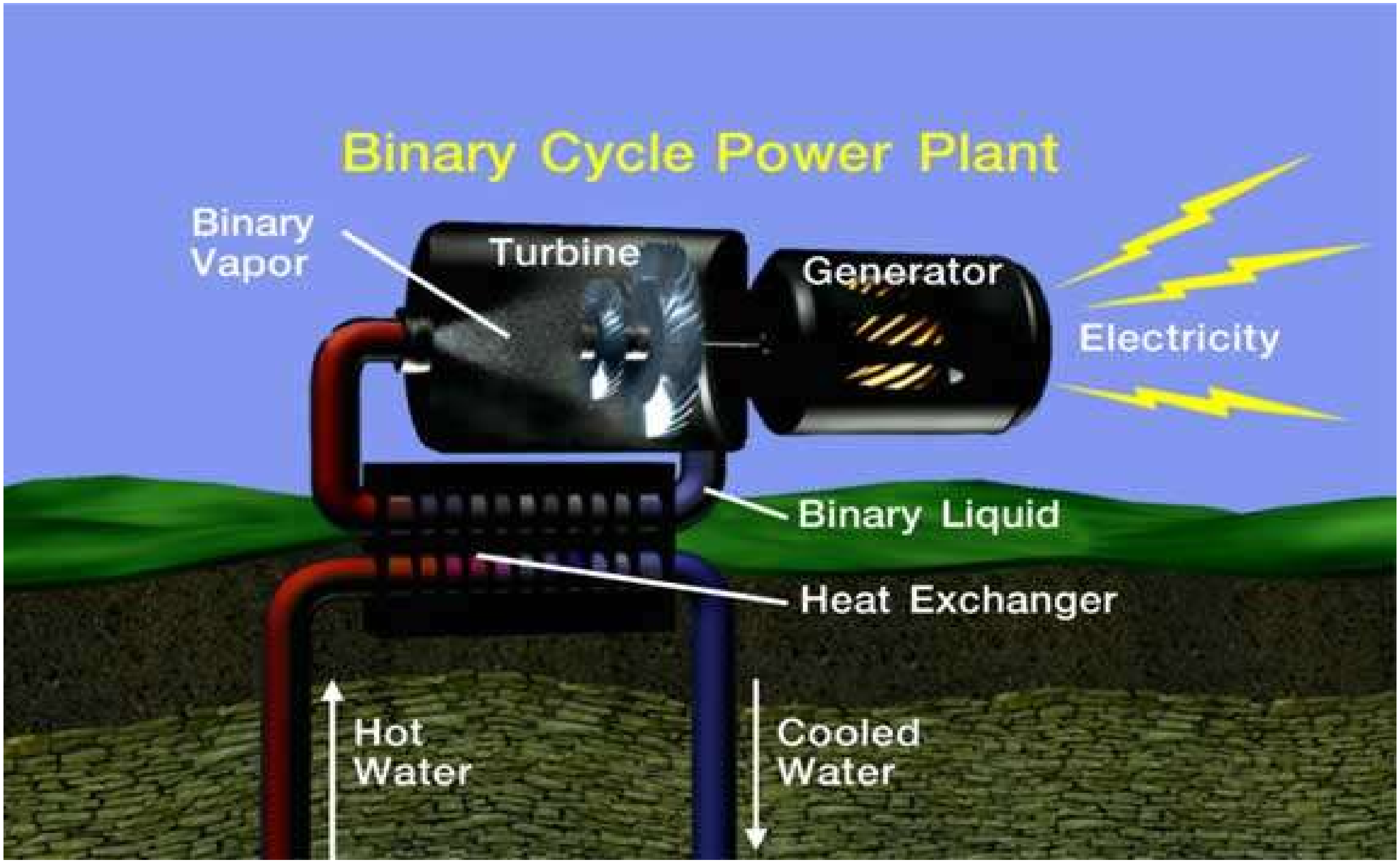


Flash Binary Plant, Upper Mahiao (125 MWe)

Ronald DiPippo: Geothermal power plants: Elsevier 2008

Binary cycle power plant

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



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Binary conversion cycles

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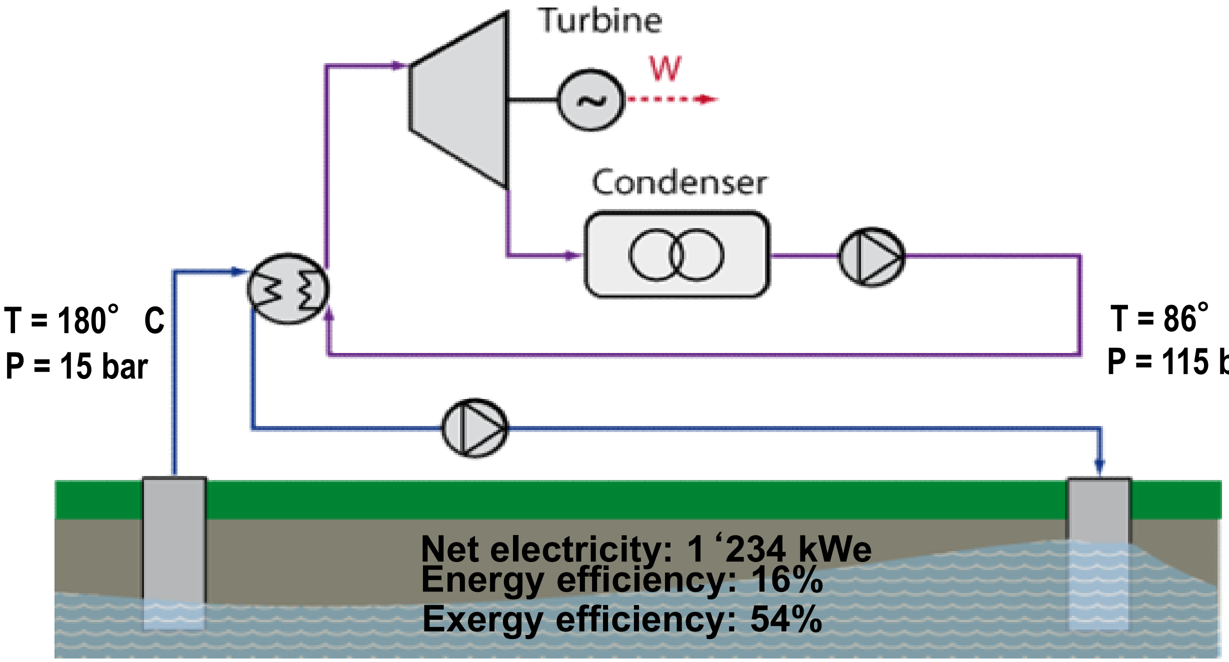
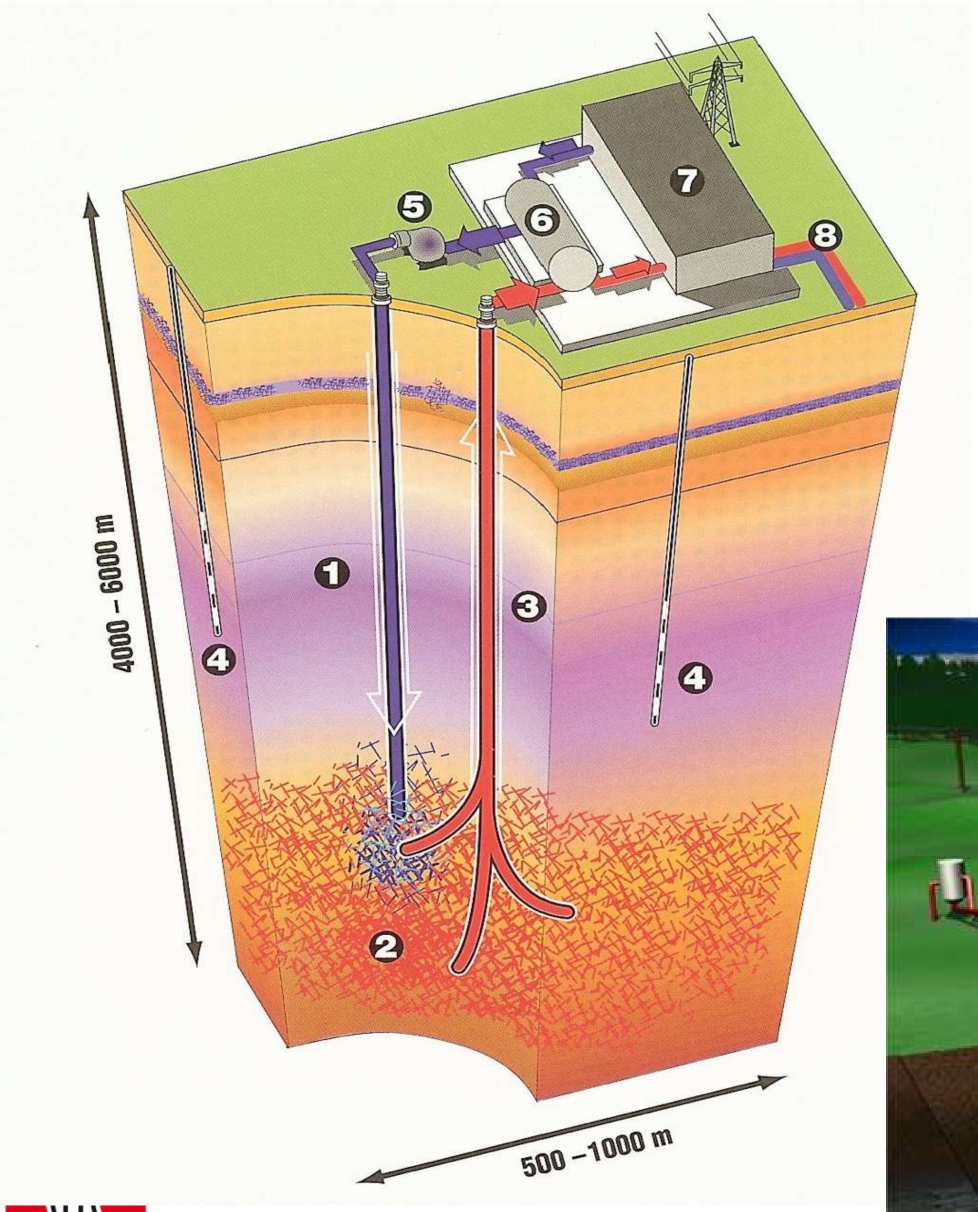
- Heat transfer occurs between the geofluid and a secondary fluid
- Use of organic fluids (**Organic Rankine cycles - ORC**) or mixture of water and ammonia (**Kalina cycles**)
- Temperature lower limit: 70-90°C (uses exist up to 200°C)
- No emissions of geofluid to atmosphere

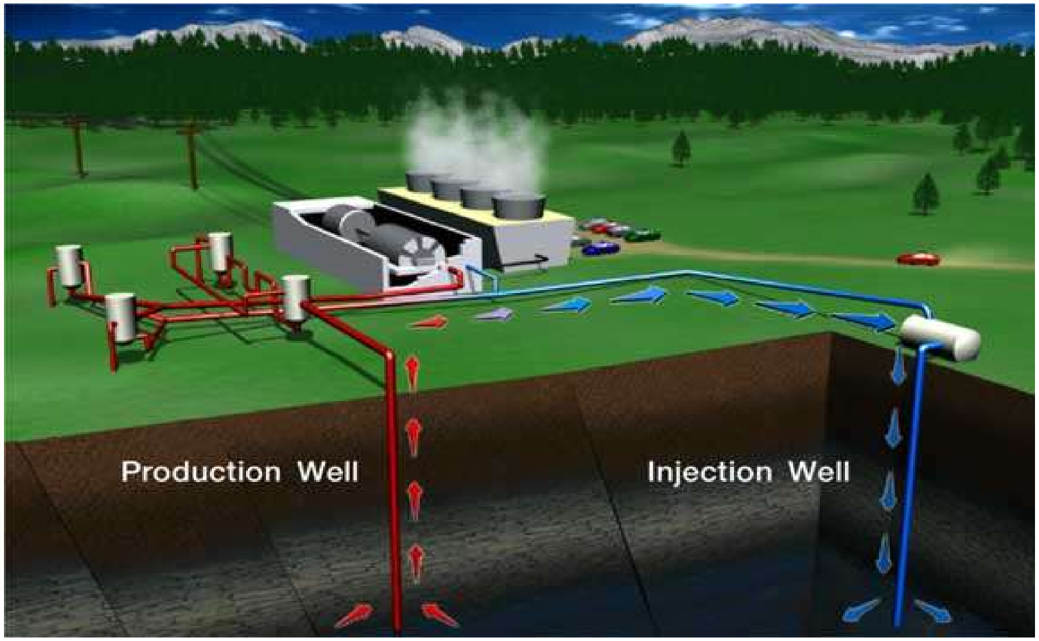


Hot *dry* rock (HDR) – or Deep Heat Mining (DHM)

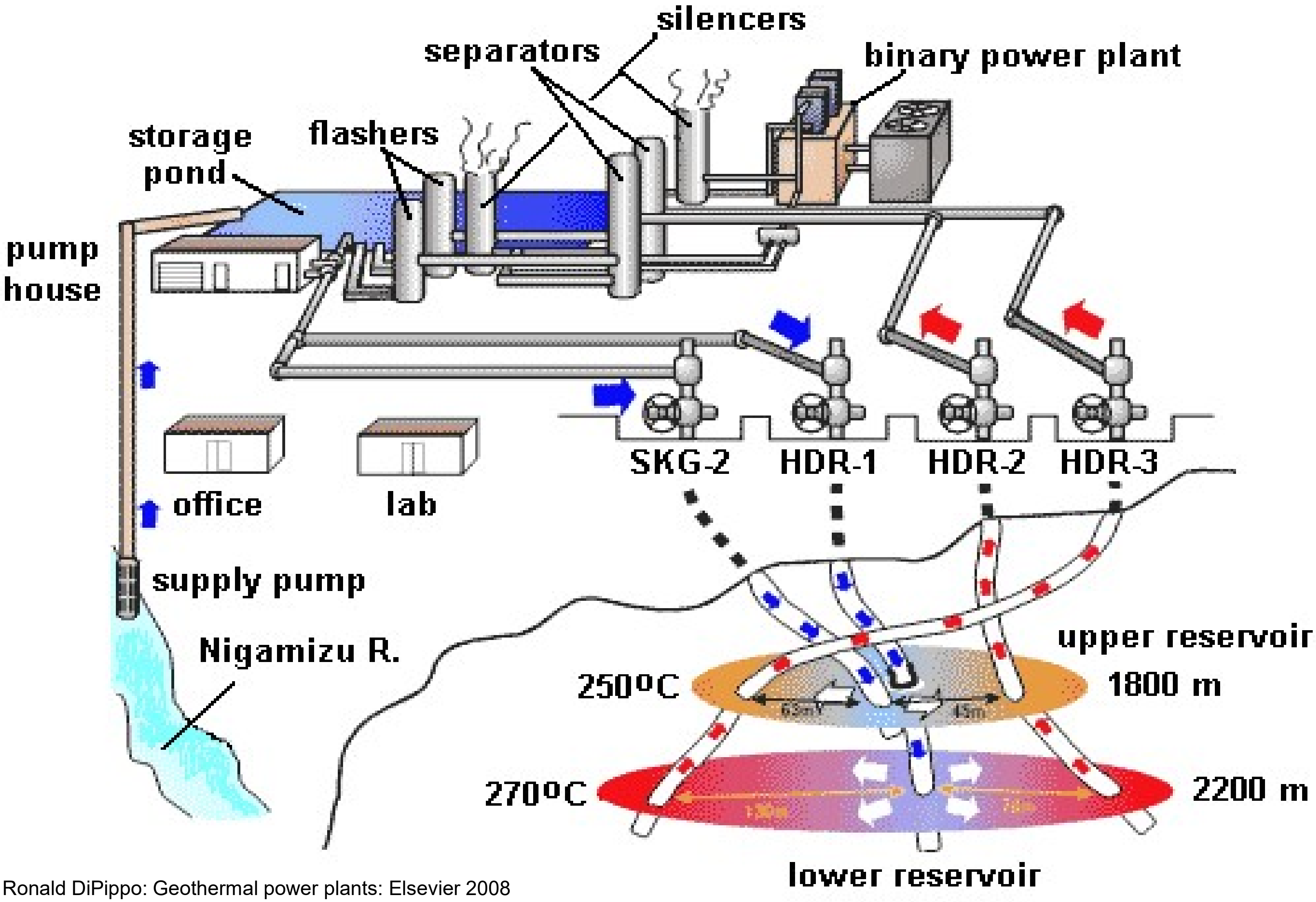
→ *unsustainable*



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

Combined conversion cycles

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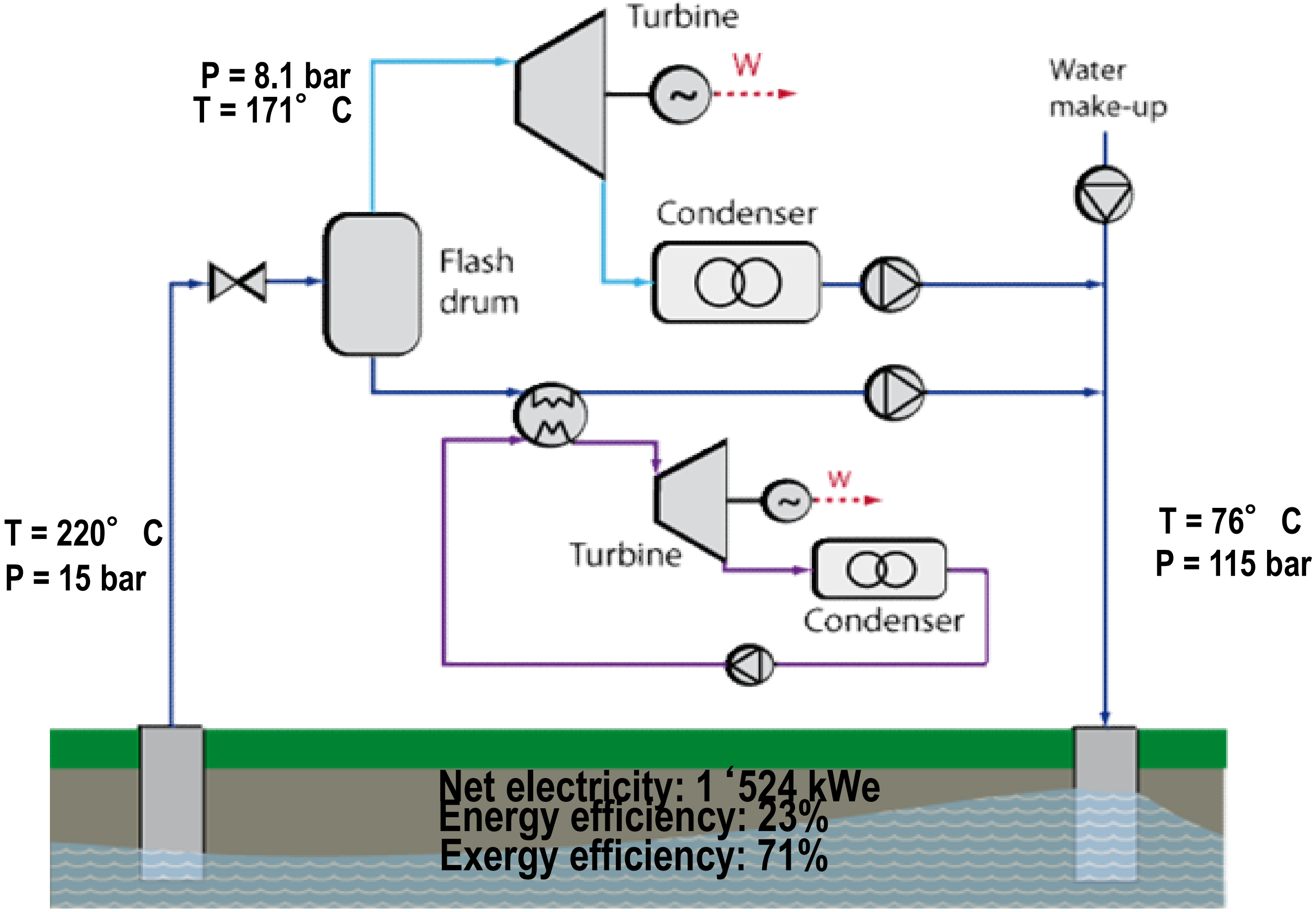
To increase the electrical efficiency

- Flash system with bottoming ORC

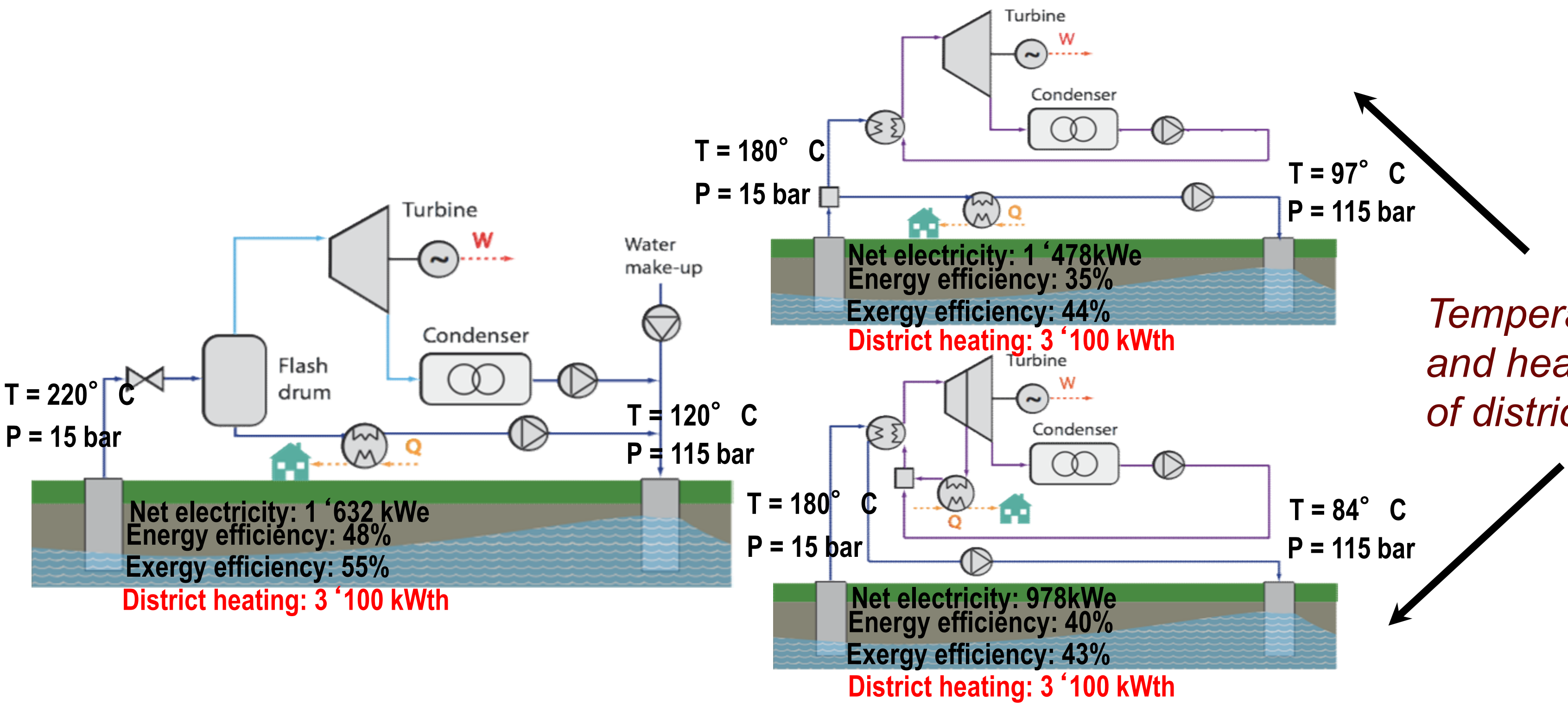


Net electricity: 1 ‘524 kWe
Energy efficiency: 23%
Exergy efficiency: 71%

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)



T = 220° C
P = 15 bar

T = 120° C
P = 115 bar

Net electricity: 1 ‘632 kWe
Energy efficiency: 48%
Exergy efficiency: 55%
District heating: 3 ‘100 kWth

T = 180° C
P = 15 bar

T = 97° C
P = 115 bar

Net electricity: 1 ‘478kWe
Energy efficiency: 35%
Exergy efficiency: 44%
District heating: 3 ‘100 kWth

T = 180° C
P = 15 bar

T = 84° C
P = 115 bar

Net electricity: 978kWe
Energy efficiency: 40%
Exergy efficiency: 43%
District heating: 3 ‘100 kWth

Temperature levels and heat loads of district heating

Temperature level usage

Electricity generation
Heat (industry, buildings)
Cogeneration

Direct heat use

Heat pumps for
building heating

Enhanced Geothermal Systems

EGS :
3’000 - 10’000m*
90 - 350°C

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

•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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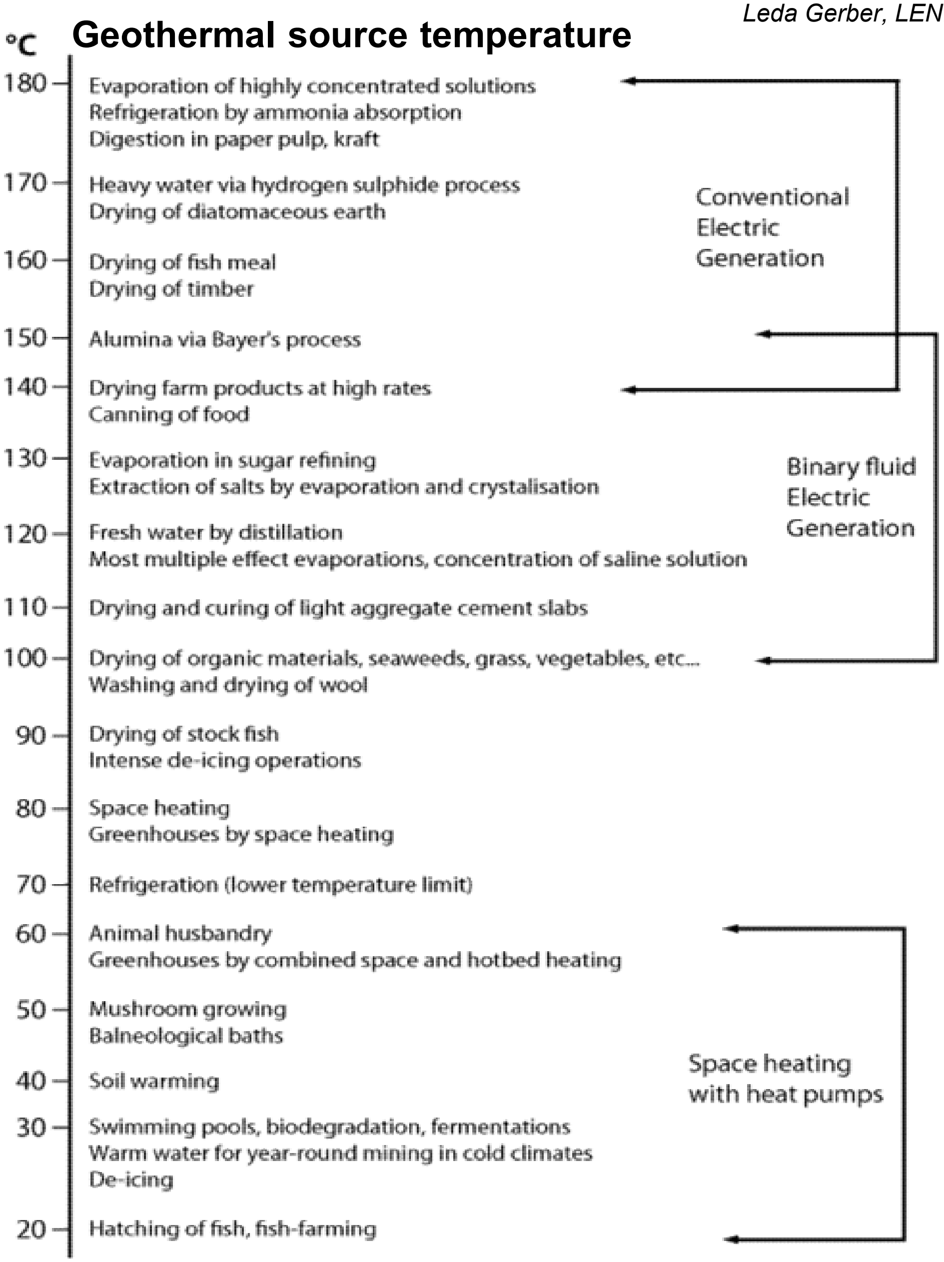


180	Evaporation of highly concentrated solutions Refrigeration by ammonia absorption Digestion in paper pulp, kraft
170	Heavy water via hydrogen sulphide process Drying of diatomaceous earth
160	Drying of fish meal Drying of timber
150	Alumina via Bayer’s process
140	Drying farm products at high rates Canning of food
130	Evaporation in sugar refining Extraction of salts by evaporation and crystalisation
120	Fresh water by distillation Most multiple effect evaporations, concentration of saline solution
110	Drying and curing of light aggregate cement slabs
100	Drying of organic materials, seaweeds, grass, vegetables, etc... Washing and drying of wool
90	Drying of stock fish Intense de-icing operations
80	Space heating Greenhouses by space heating
70	Refrigeration (lower temperature limit)
60	Animal husbandry Greenhouses by combined space and hotbed heating
50	Mushroom growing Balneological baths
40	Soil warming
30	Swimming pools, biodegradation, fermentations Warm water for year-round mining in cold climates De-icing
20	Hatching of fish, fish-farming

Different forms

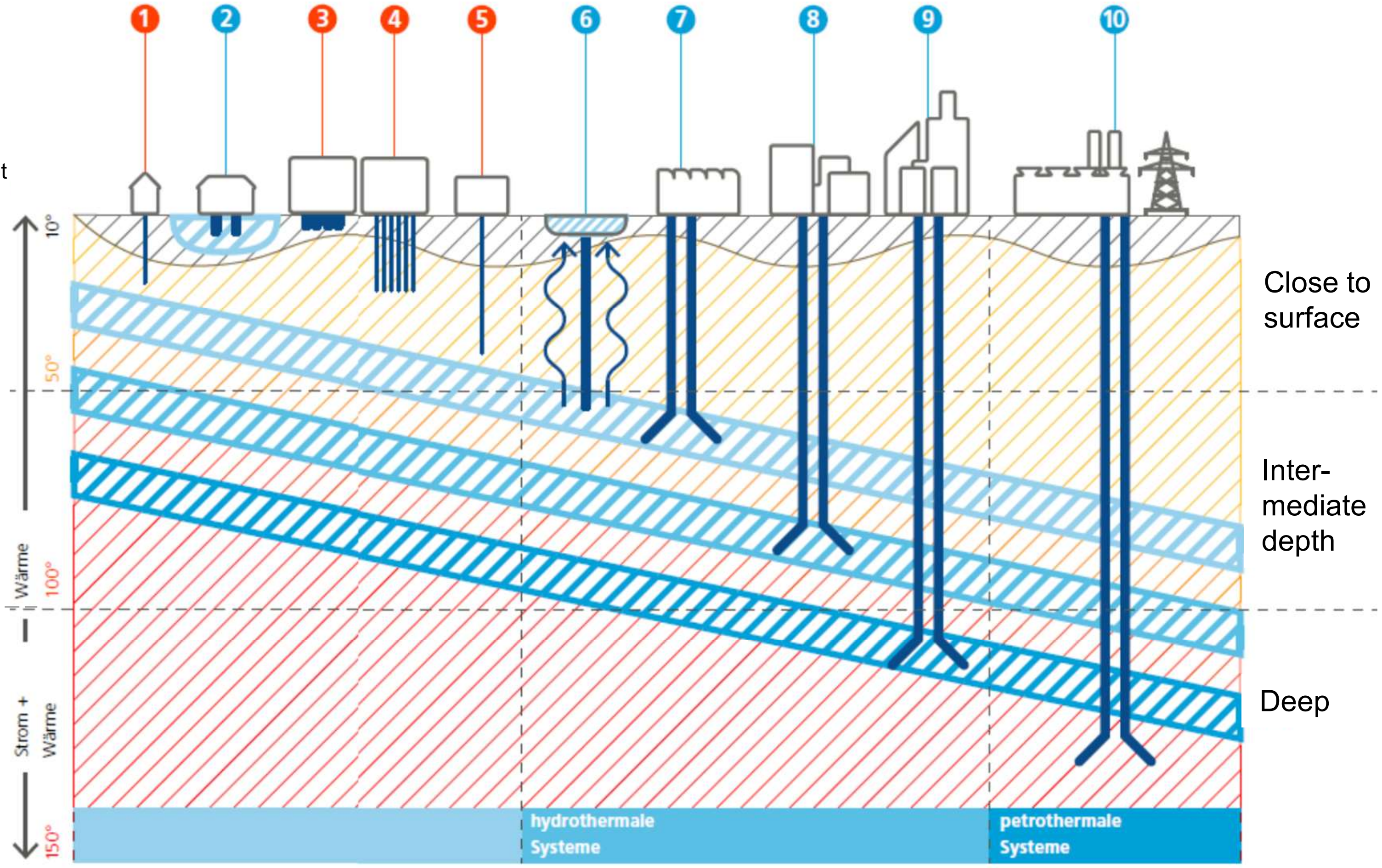
① Earth heat probe/geotherm. basket
② Groundwater use
③ Geo-structures
④ Earth heat probe, field
⑤ Deep earth heat probe

⑥ Thermal bath

Hydrothermal, intermed. depth:
⑦ Heat for industry, agriculture
⑧ Heat for heating and hot water

Hydrothermal, deep:
⑨ Heat and power

⑩ Petrothermal:
Heat and power



Close to surface

Inter-mediate depth

Deep

● Open cycle

● Closed cycle

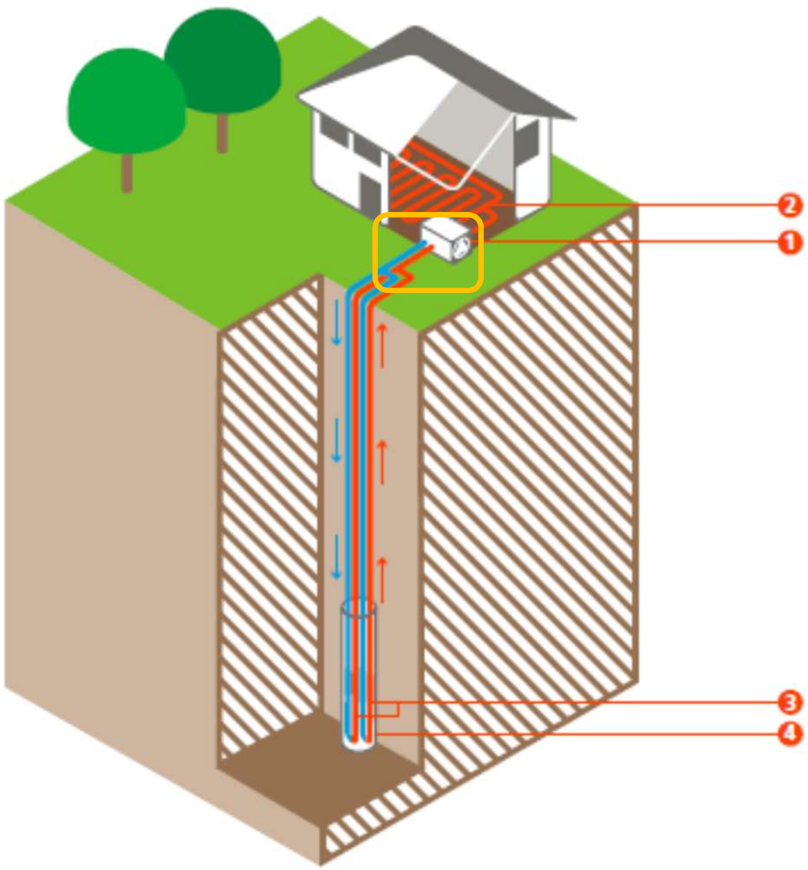
Energie Schweiz: Geothermie in der Schweiz, 2006

Close to surface

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

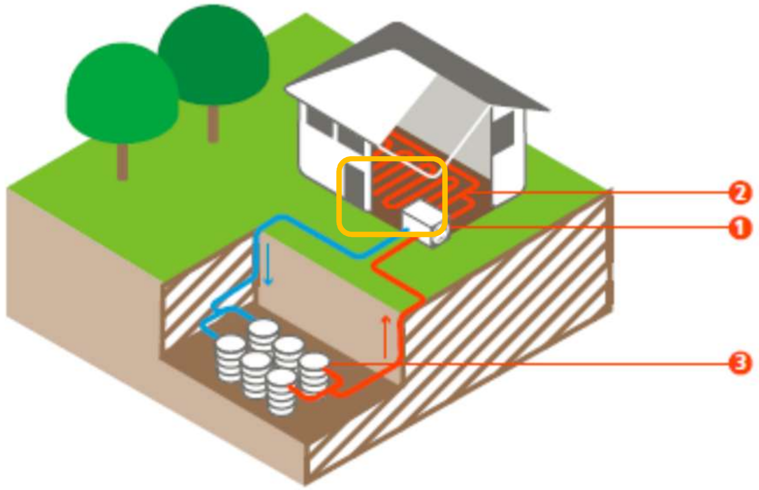
Geothermal heat probe

① Heat pump
② Floor heating
③ Heat exchanger (double U-tube)
④ Bore hole (<20 cm diameter)



Geothermal heat basket

① Heat pump
② Floor heating
③ Geothermal baskets

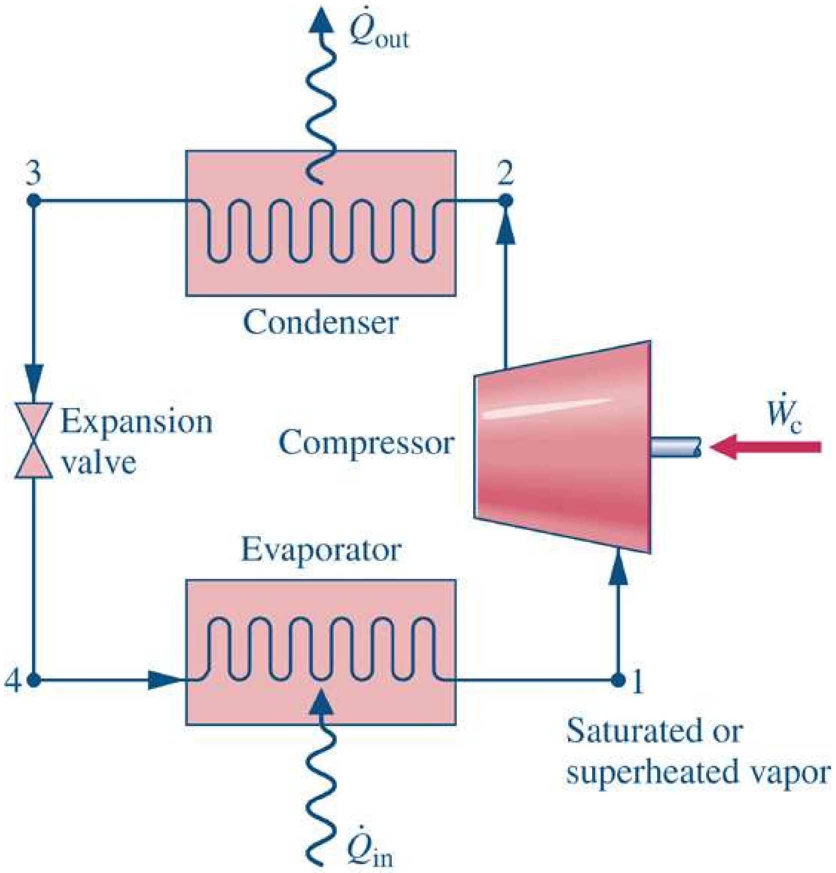


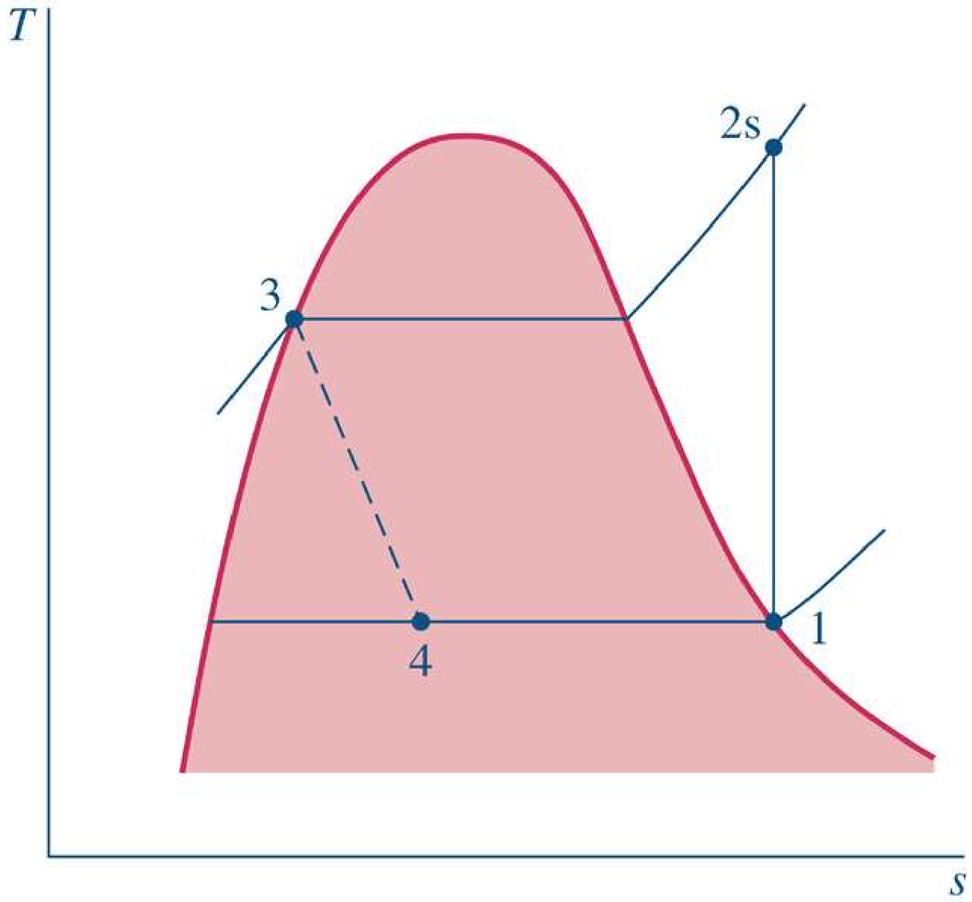
Depth:
1.5 to 4 m for geothermal baskets
50 to 250 m for heat probe

Temperature: 5-20°C

Heat pump systems

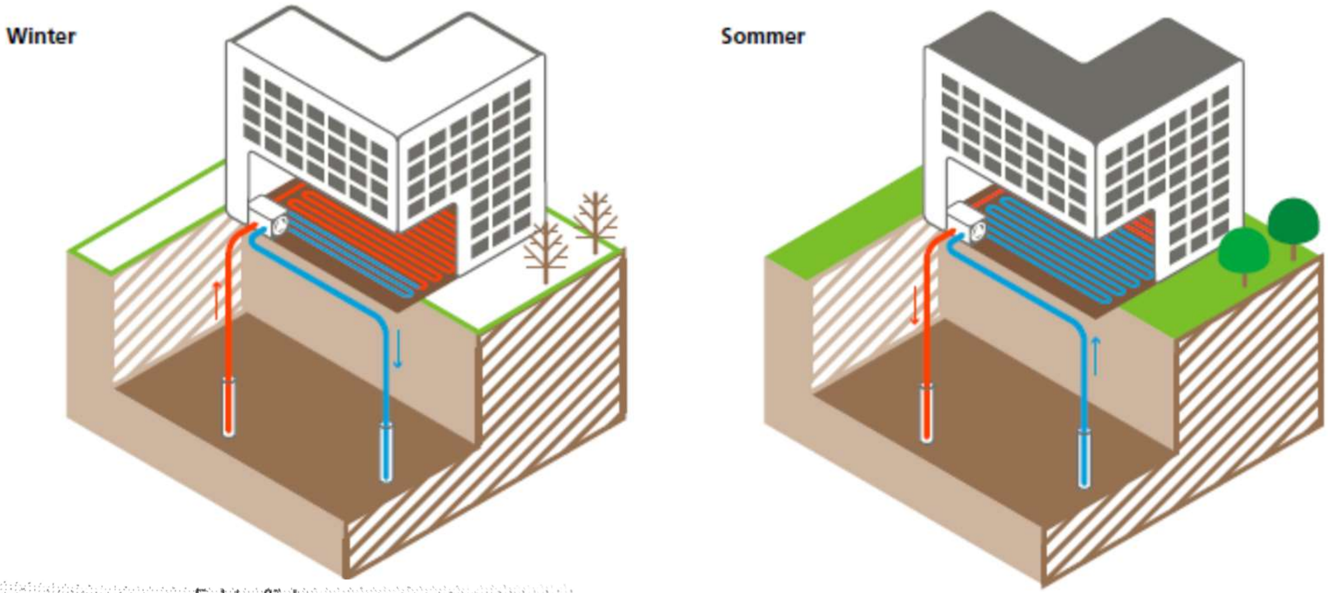
- Vapor-compression heat pumps:

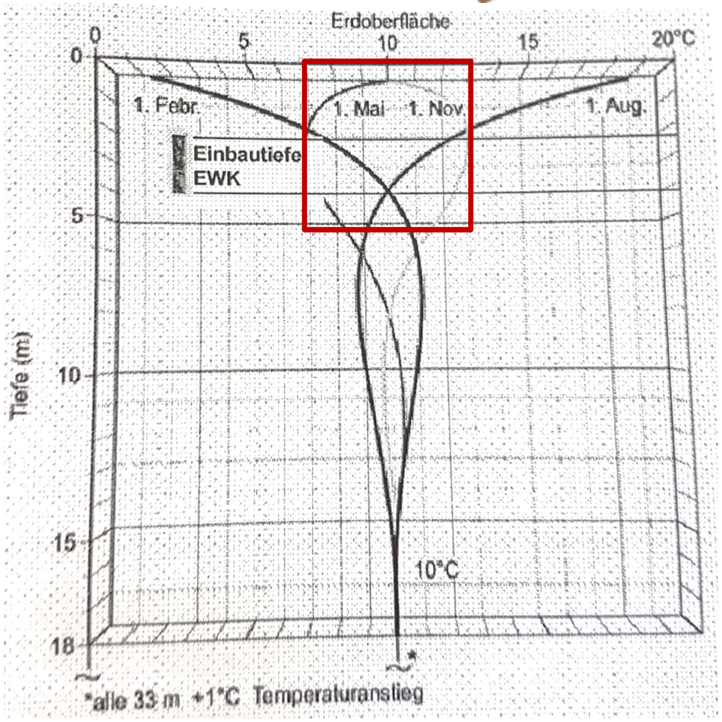




Close to surface

- 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 hoses, 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

Summary

- Geothermal power plants are clean, reliable and provide **baseload** for decades or centuries, on sites with *thermal anomalies* (volcanic, tectonic).

- 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%)