IPESE
Industrial Process and Energy Systems Engineering

École Polytechnique Fédérale de Lausanne

Geothermal Energy

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Energy Conversion 2014/2015 – Prof. François Maréchal

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Outline

- **Introduction**
  - What is geothermal energy?
  - The “value” of heat: applications of geothermal energy
  - Geothermal today
- **Resources**
  - Types, availability and cost of geothermal resources
  - Future potential
- **Geothermal power plants**
  - Using the heat above the ground
  - Main energy conversion cycles: key characteristics and thermo-economic performance
- **Take home message**

Introduction

Introduction

What is geothermal energy?

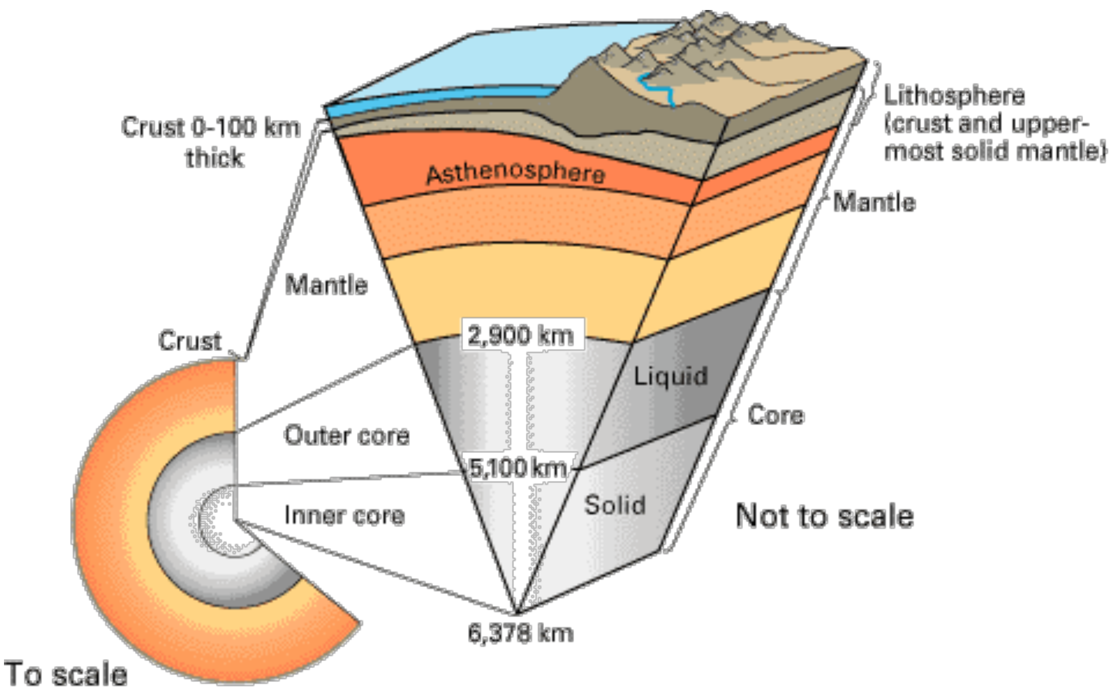
Sources:
[1] Online Etymology dictionary: http://www.etymonline.com
[2] USGS, http://pubs.usgs.gov/gip/dynamic/inside.html
[3] http://en.wikipedia.org/wiki/Geothermal_gradient, adapted from Boehler, R. (1996). Melting temperature of the Earth's mantle and core: Earth's thermal structure. Annual Review of Earth and Planetary Sciences, 24(1), 15–40.

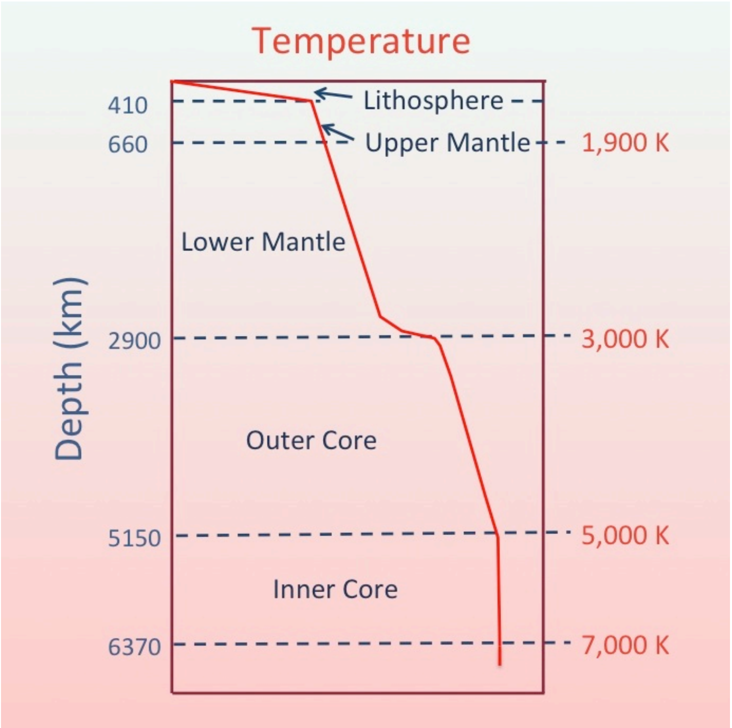
"Geo"[1] → From "γη" ("ge", Greek) = "the Earth"

\+

"Thermal"[1] → From "θέρμη" ("thermé", Greek) = "heat"

Heat from the original formation of the planet and from radioactive decay of materials





The "value" of heat

Based on the notion of exergy, the "value" of a heat source depends on its temperature. The Carnot factor θ_c of a source at temperature T with respect to a reference temperature T_0 (normally ambient, all units in Kelvin):

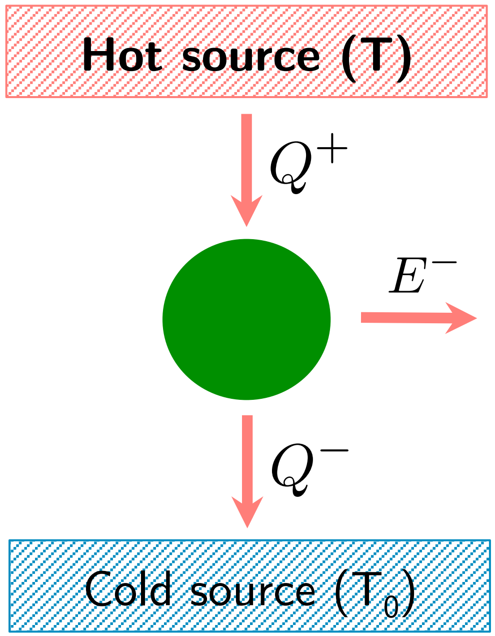
$$\theta_c = 1 - \frac{T_0}{T} \quad (T > T_0)$$

In the case of an ideal engine:

$$\varepsilon = \frac{E^-}{Q^+}$$

$$E^- = Q^+(1 - \frac{T_0}{T}) = Q^+\theta_c$$

A higher temperature T of the hot source allows for a higher efficiency → higher work production



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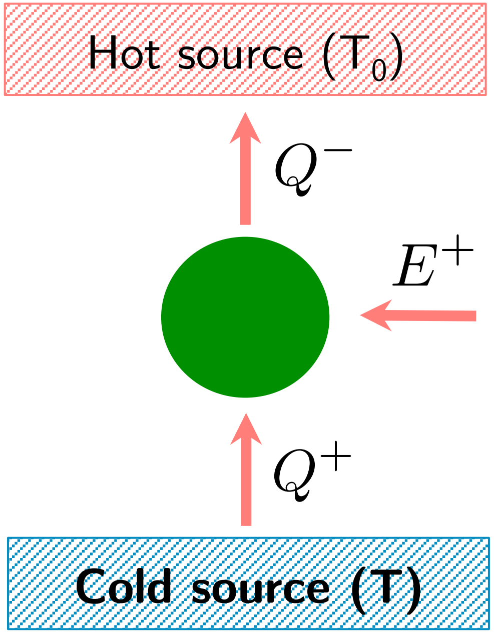
$$\theta_c = 1 - \frac{T}{T_0} \quad (T < T_0)$$

In the case of an ideal heat pump (for heating):

$$\varepsilon = COP_h = \frac{Q^-}{E^+}$$

$$E^+ = \frac{Q^-}{COP_h} = \frac{Q^-}{\frac{T_0}{T_0 - T}} = \frac{Q^-}{\frac{1}{\theta_c}} = Q^- \theta_c$$



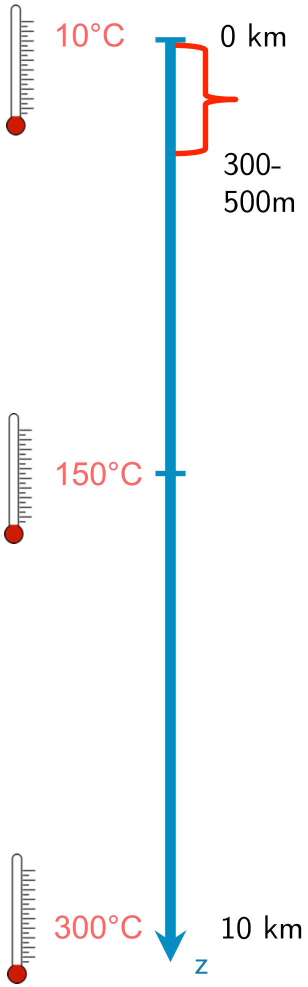
A higher temperature T of the cold source allows for a higher efficiency → lower work (electricity) consumption

Introduction

Sources:
[1] S. Hirschberg et al., Energy from the Earth, 2015 (pp. 11,26)
[2] IEA, Technology Roadmap - Geothermal Heat and Power, 2011 (p. 7)

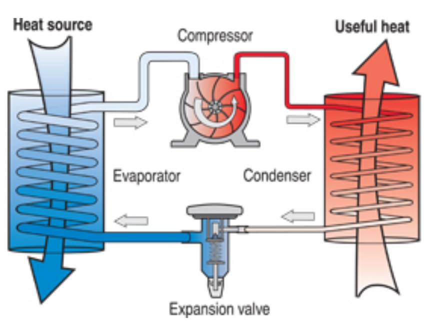
Applications of geothermal energy

Geothermal gradient: rate of temperature increase with depth [K/m] due to conductive heat transfer in the crust. In Switzerland about 30 K/km[1].

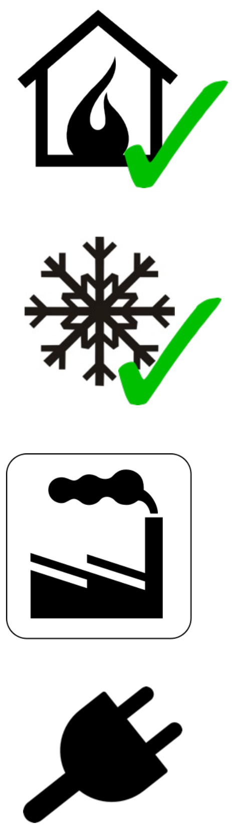


Ground Source Heat Pumps (GSHP)

- Low-T shallow systems make use of the stable temperature of the ground, of 10-20°C in moderate climates.
- More efficient heating/direct cooling.
- Developed in the 1940s.
- Can store extracted heat in summer and make this heat useful again in the heating mode in winter.



End-uses



Sources:
[1] S. Hirschberg et al., Energy from the Earth, 2015 (pp. 11,26)
[2] IEA, Technology Roadmap - Geothermal Heat and Power, 2011 (p. 7)

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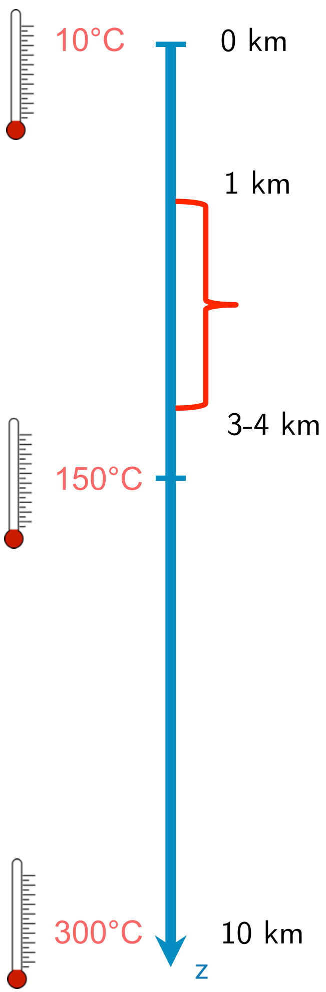
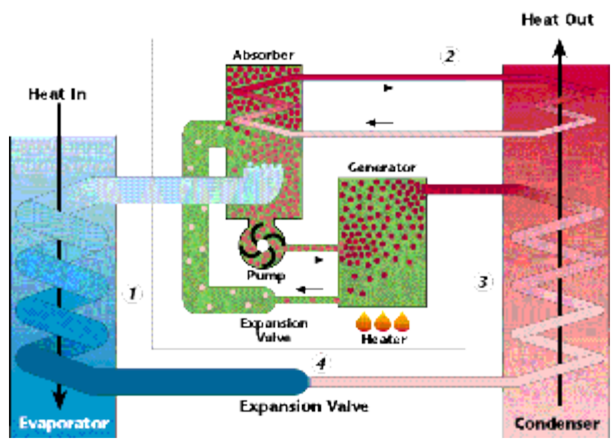
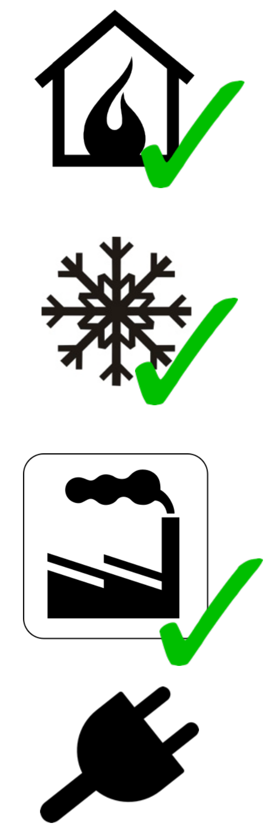


Direct use

- "Low-enthalpy" applications, usually with deep aquifers
- District heating for buildings
- Possibility of cascade usage (low-T industry, greenhouses,...)
- Cooling with absorption heat pumps



End-uses



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[2] IEA, Technology Roadmap - Geothermal Heat and Power, 2011 (p. 7)

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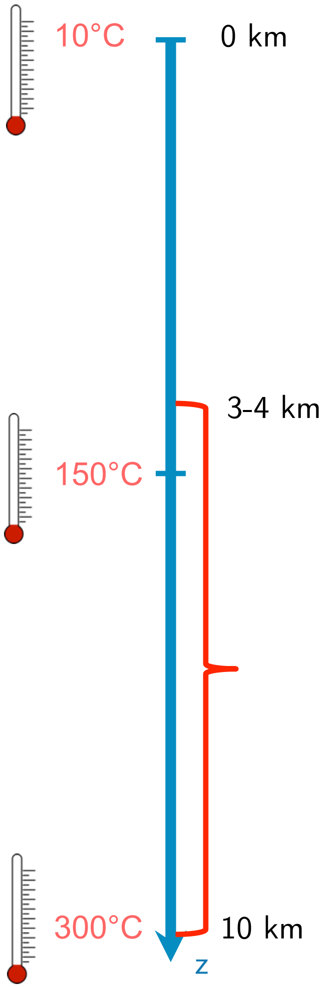
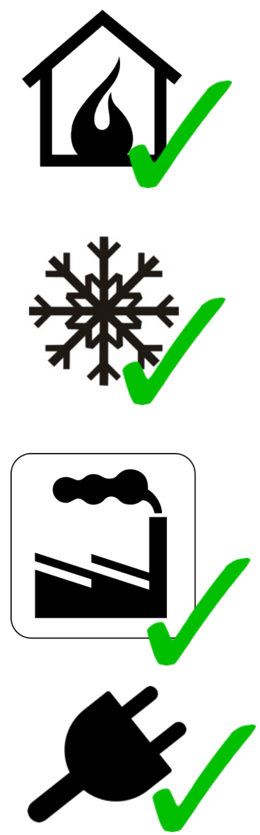


Electricity production & cogeneration

- High-enthalpy applications
- Use of geothermal heat in energy conversion cycles for electricity and heat production (cogeneration)

Geothermal heat can be used for different purposes (not only electricity!), based on its temperature level. The other key aspect is the type of geothermal resource.

End-uses



Sources:
[1] IEA, Key World Energy Statistics 2013
[2] IEA, Technology Roadmap - Geothermal Heat and Power, 2011 (p. 9)
[3] IPCC, Special Report on Renewable Energy Sources and Climate Change Mitigation, 2011
[4] Lund et al., Direct utilization of geothermal energy 2010 worldwide review, 2011.

- World energy consumption: 152500 TWh/y (2011)[1]
- 0.1% of global primary energy consumption (2008)[3]
- Electricity: 10.7 GW_e installed, 67.2 TWh_e/y (2009)[2]
- Heat: 48.5 GW_{th} installed, 117.7 TWh_{th}/y (2010)[4]

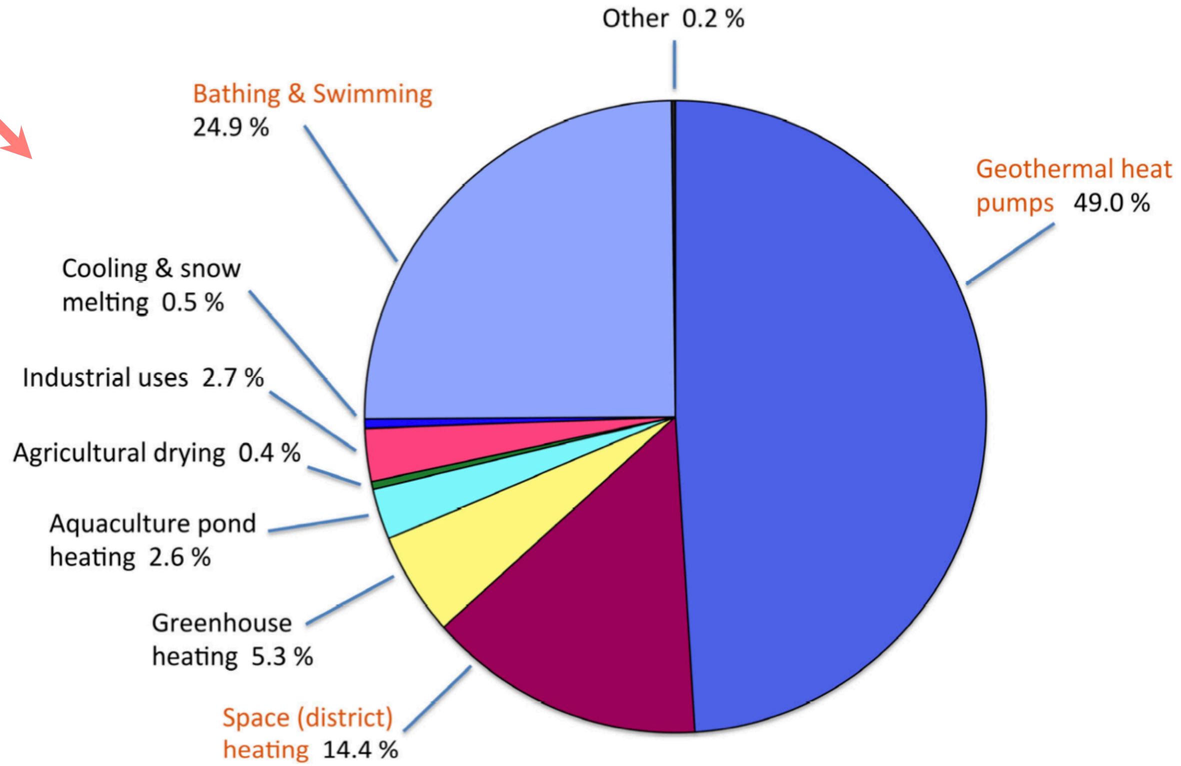
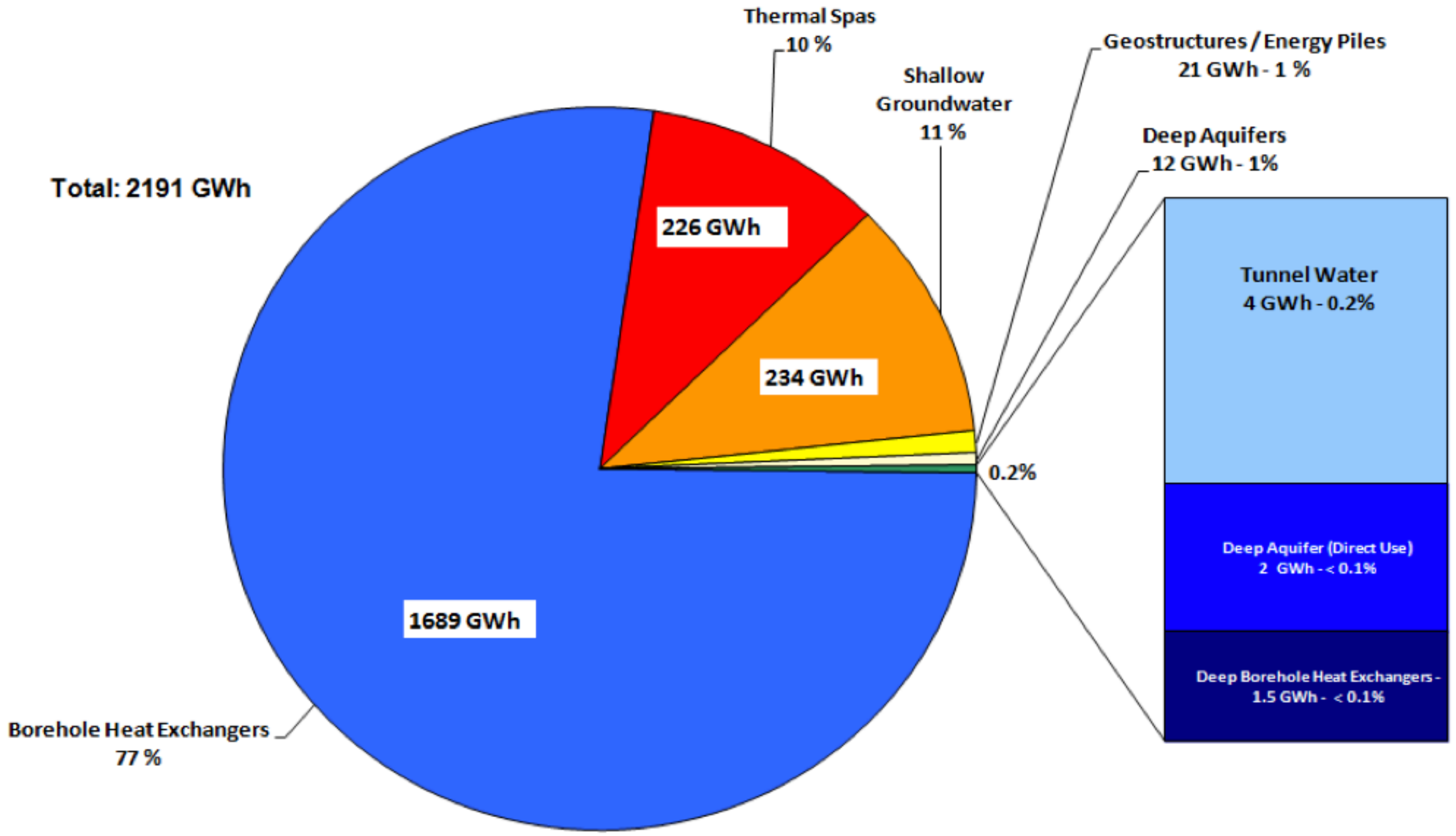


***Figure 4:** Direct uses of geothermal heat worldwide in 2010 (Lund et al., WGC 2010).*

Sources:
[1] OFEN, Energy statistics 2012
[2] S. Hirschberg et al., Energy from the Earth, 2015 (p. 12)

Geothermal today - Switzerland

- Swiss final energy consumption: 237 TWh/y (2011)[1]
- Heat 2.2 TWh_{th}, no electricity (2012)[2]



Sources:
[1] S. Hirschberg et al., Energy from the Earth, 2015 (pp. 15)

Geothermal today – Electricity production

- First power plant in Lardarello (Italy) in 1904
- Significant share of total electricity demand in Iceland (25%), El Salvador (22%), Kenya and the Philippines (17% each), and Costa Rica (13%)
- US leader in absolute value, Italy in Europe (0.88 GW_e)

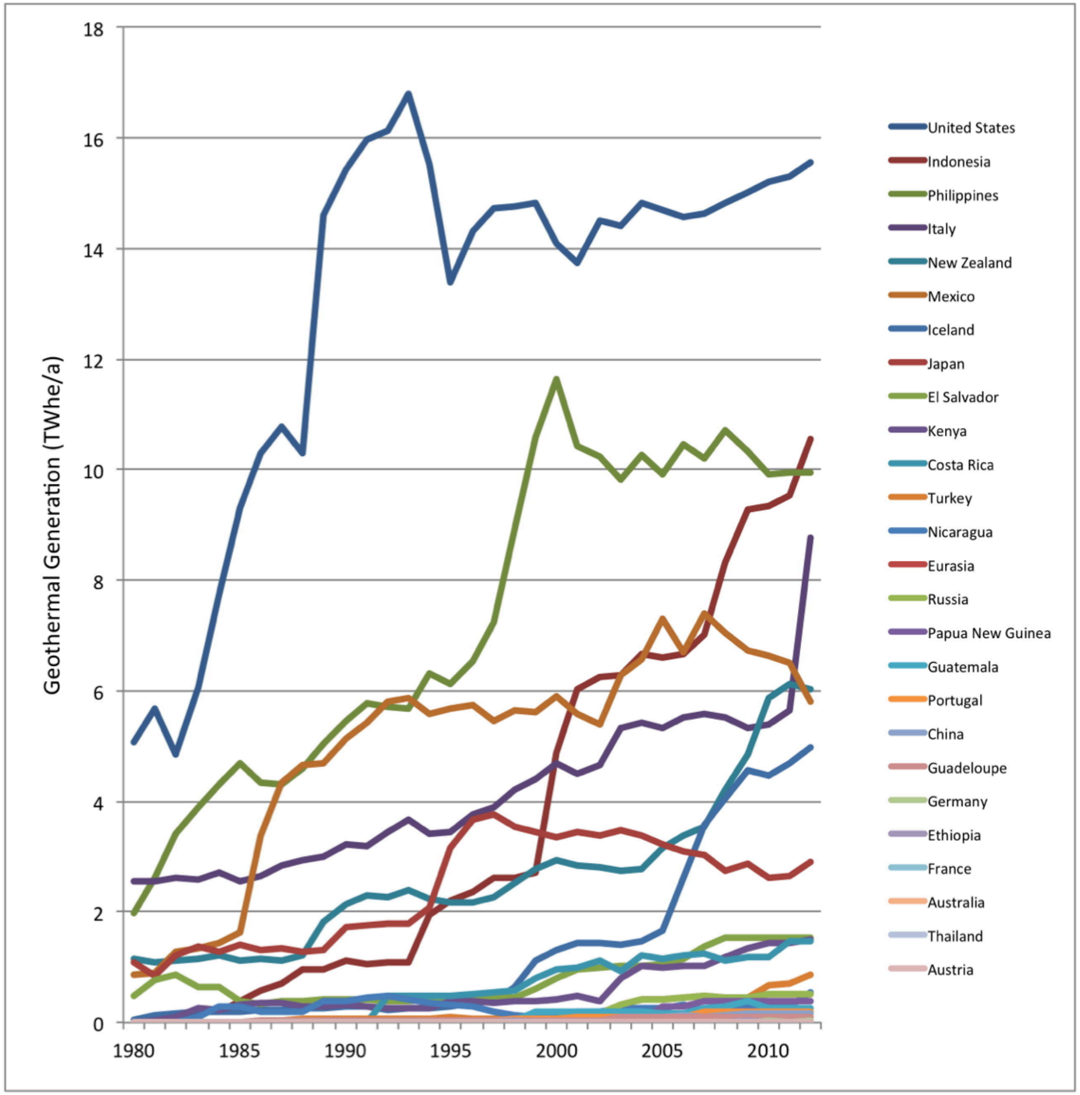


***Figure 8**: Geothermal generation by nation*[6].

Resources

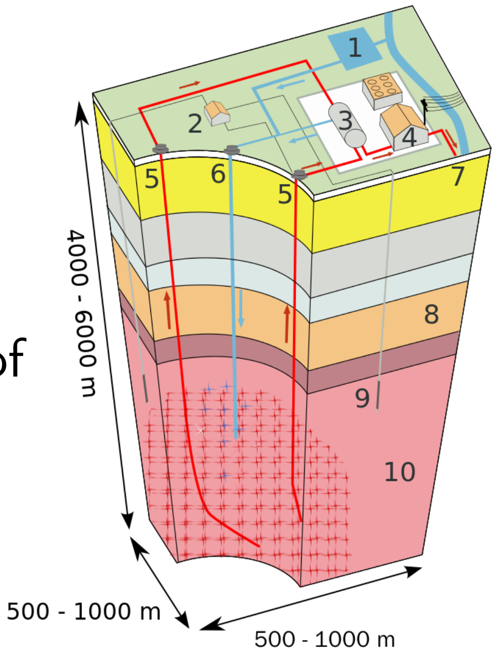
Sources:
[1] IEA, Technology Roadmap - Geothermal Heat and Power, 2011 (pp. 9-11)
[2] R. Dipippo, Geothermal power plants, 2012 (pp. 9-15)
[3] Image: http://en.wikipedia.org/wiki/Enhanced_geothermal_system

Types of geothermal resources

Based on their characteristics, geothermal resources can be classified into different types:

- Hydrothermal resources: high-temperature (water/steam at 100-300°C), "hot springs". Extremely location-dependent (e.g. tectonic plate boundaries). As of 2007, only ones to be commercially developed for electricity production[2].

- Hot Dry Rock: high temperature but low permeability. Hydraulic fracturing used to enhance permeability → Enhanced Geothermal Systems (EGS)
- Geopressure: very high pressure, high T, dissolved methane. Location-specific (Gulf of Mexico).
- Magma energy: based on solidification and fracturing of magma. Major technical difficulties.
- Deep hydrothermal: 2.5-5 km deep aquifers. Temperature depending on geothermal gradient.



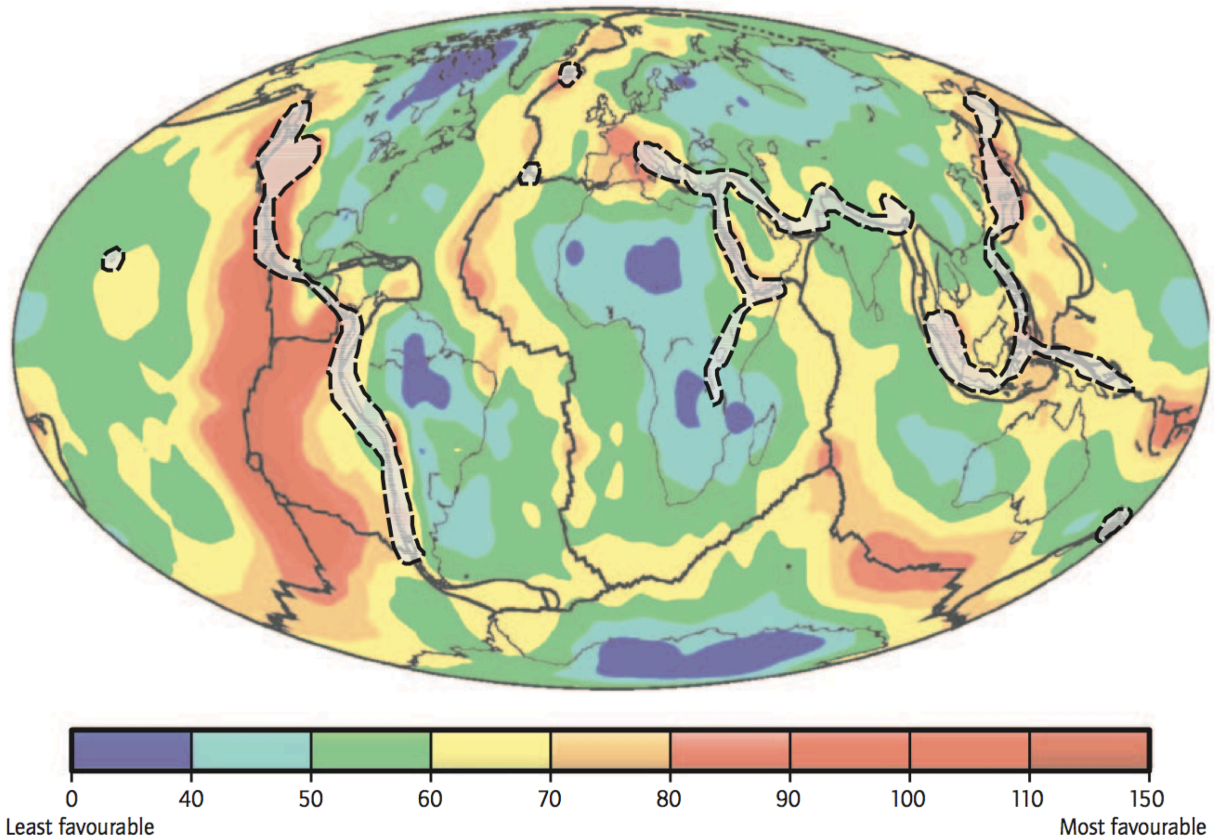
Resources

Sources:
[1] IEA, Technology Roadmap - Geothermal Heat and Power, 2011 (p. 10)

Availability of geothermal resources

Hydrothermal (as geopressure and magma energy) is very location-dependent.

Figure 2: World resource map of convective hydrothermal reservoirs



Note: Convective hydrothermal reservoirs are shown as light grey areas, including heat flow and tectonic plates boundaries.

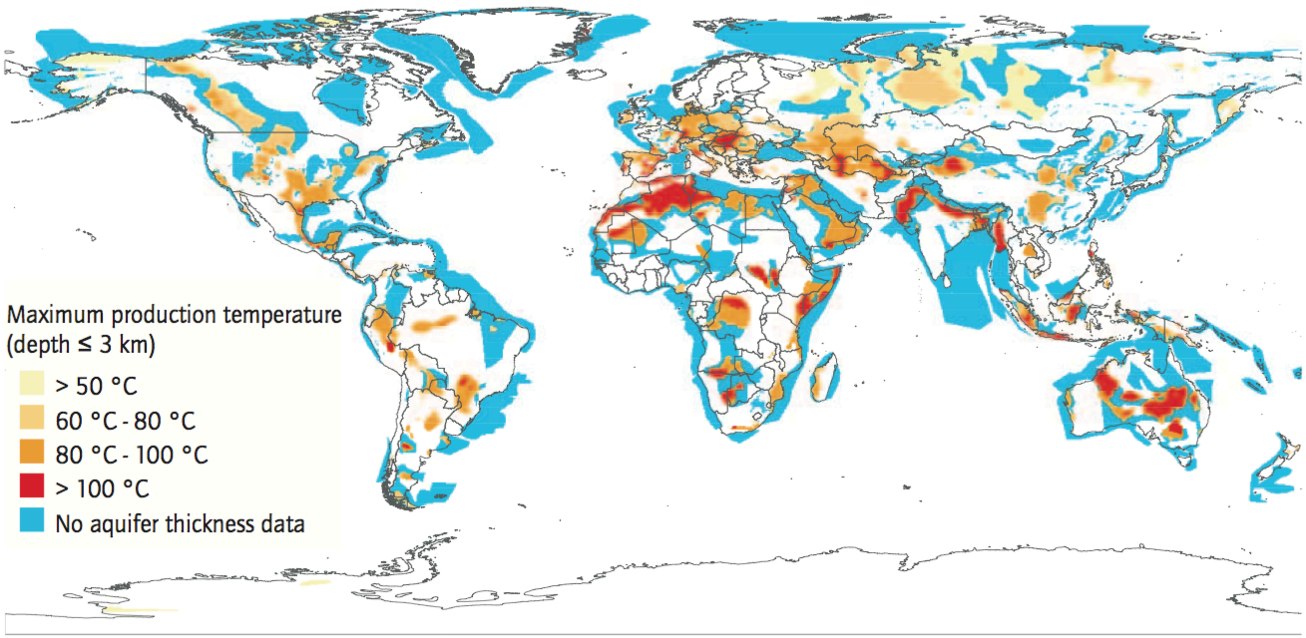
Source: Background figure from (Hamza *et al.*, 2008), adjustments from (IPCC, forthcoming).

Sources:
[1] IEA, Technology Roadmap - Geothermal Heat and Power, 2011 (p. 11)
[2] S. Hirschberg et al., Energy from the Earth, 2015 (p. 13)

Availability of geothermal resources

On the other hand, shallow resources (for GSHP) and EGSs can be widely deployed. Deep hydrothermal depends on availability of aquifers.

Figure 3: World map of deep aquifer systems



"...there has been a natural progression since these early beginnings from the use of the rarest, and highest-quality, resources to the use of lower quality, but more ubiquitous, resources..." [2]

Resources

Sources:
[1] Koenraad F. Beckers et al., Levelized Costs of Electricity and Direct-Use Heat from Enhanced Geothermal Systems, 2013
[2] S. Hirschberg et al., Energy from the Earth, 2015

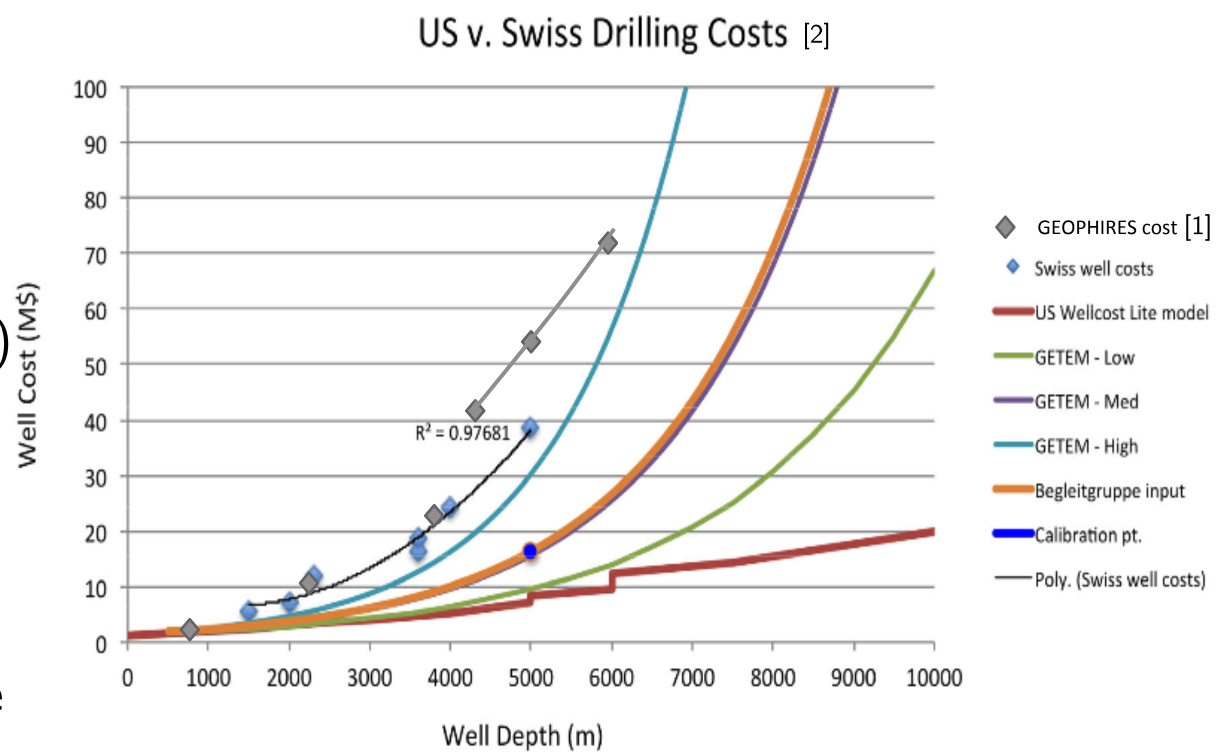
Well cost

Well construction phases[1]

- Exploration (20-30% of total Investment)
- Drilling (65-75%)
- Stimulation (0-6%)
- Fluid distribution (1-3%)

For Typical EGS[2]

- 2 exploratory wells
- 2 confirmation wells
- 1 extraction well
- 2 injection wells (1 reuse of confirmation well)



- Switzerland: 57 million USD for a 6 km well, historical data (BFE) → 20.9 million USD for a 5 km well based on drilling costs from St. Gallen
- Higher costs compared to oil&gas industry due to larger well diameter needed (higher mass flow rates)

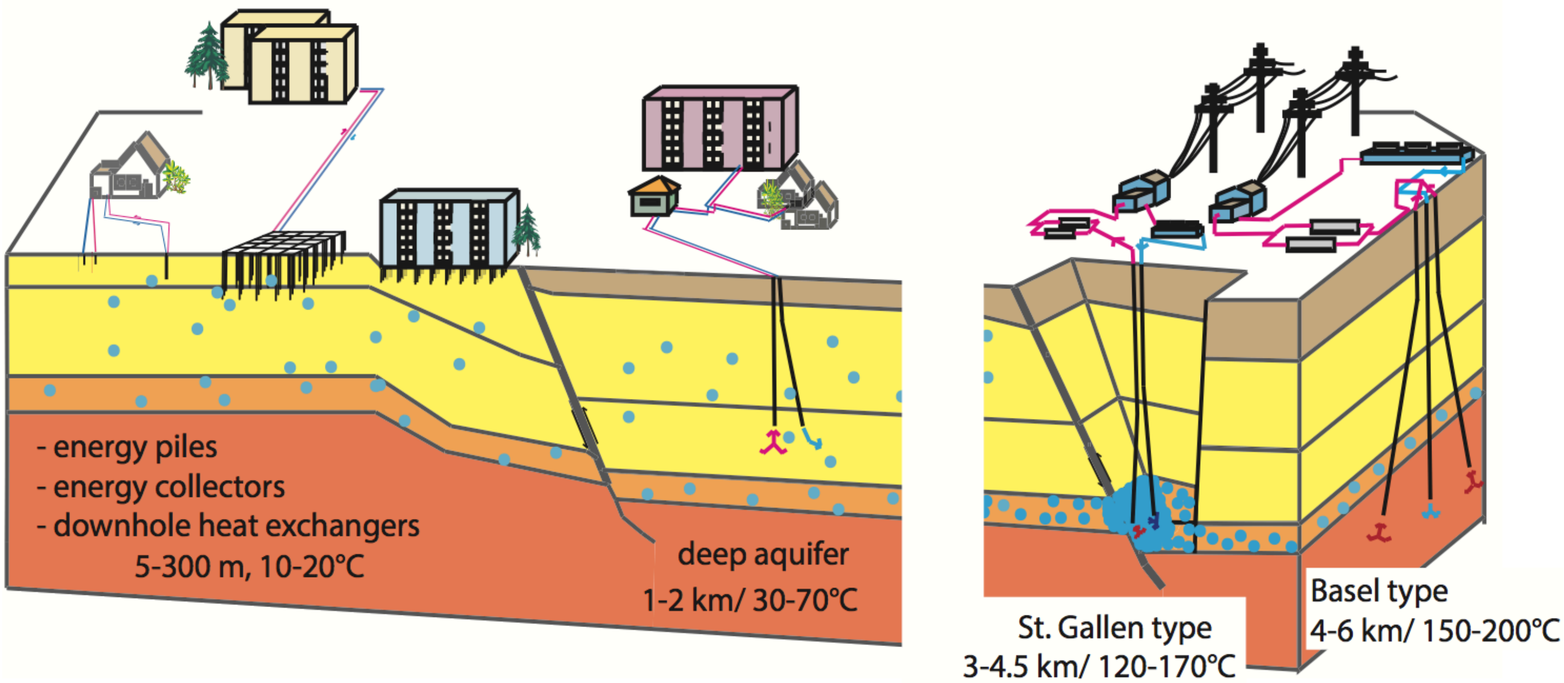
Resources

Future potential - worldwide

Sources:
[1] IEA, Technology Roadmap - Geothermal Heat and Power, 2011 (pp. 7,11)
[2] IPCC, Special Report on Renewable Energy Sources and Climate Change Mitigation, 2011
[3] S. Hirschberg et al., Energy from the Earth, 2015 (p. 26)

- World energy consumption: 152500 TWh/y (2011)[1]
- Estimated technical potential: 12500 Twh_e/y, 289000 TWh_{th}/y[1]
- IEA projection geothermal: 1400 TWh_e/y (2050)[1]
- 3% of global electricity demand, 5% of global heat demand (2050)[2]
- Typical baseload technology: constant over the year, high capacity factor

Key technologies for locations without particularly favorable geology[3]:

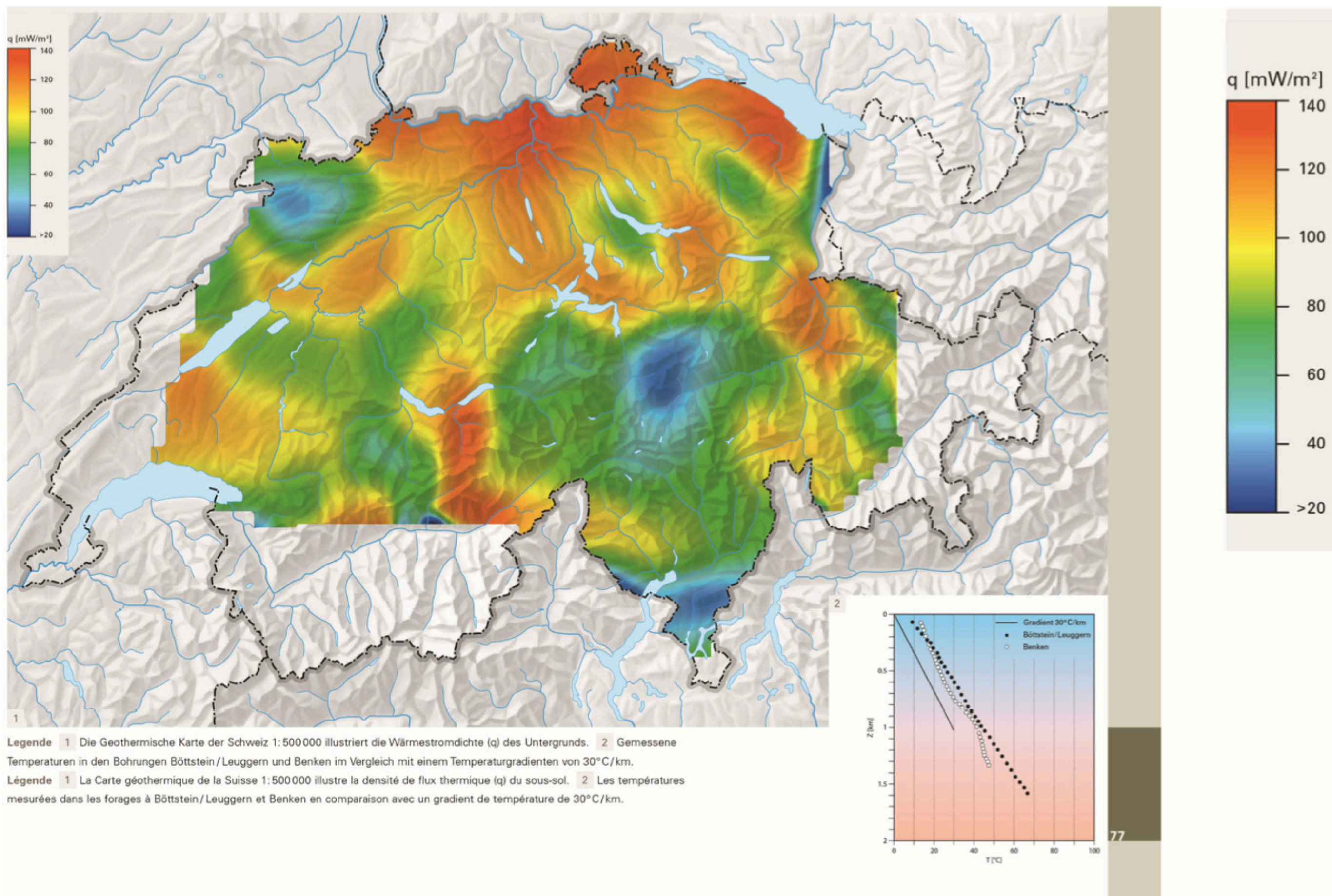


Sources:
[1] OFEN, Energy statistics 2012
[2] S. Hirschberg et al., Energy from the Earth, 2015 (p. XXXI, 27)

Future potential - Switzerland

- Swiss final energy consumption: 237 TWh/y (2011)[1]
- Estimated potential (OFEN): 4-5 Twh_e/y(2050)[2]

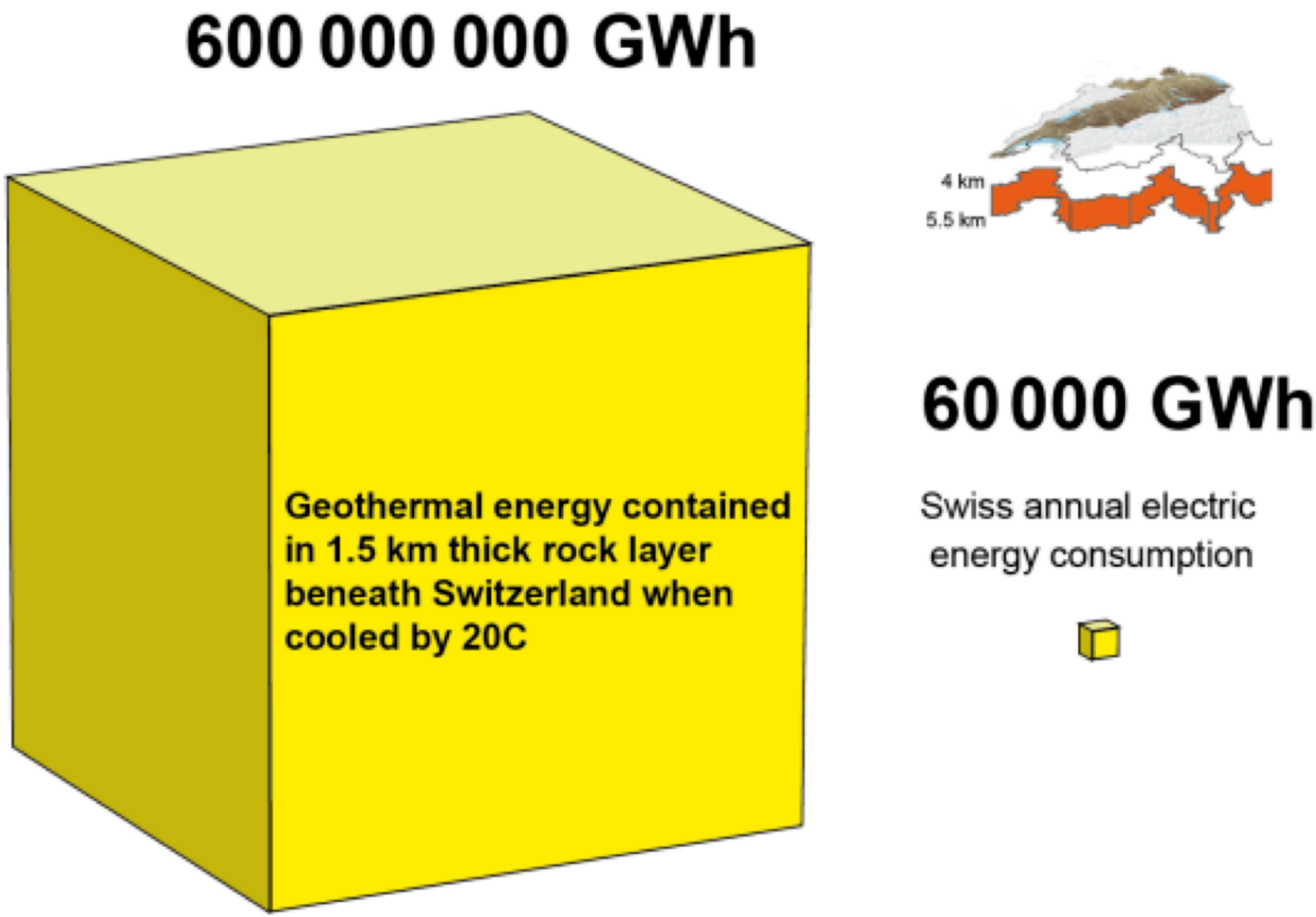
The natural, renewable heat flow through the surface of the country is 24 TWh/y[2]



Resources

Sources:
[1] S. Hirschberg et al., Energy from the Earth, 2015 (p. 29)

Future potential - Switzerland

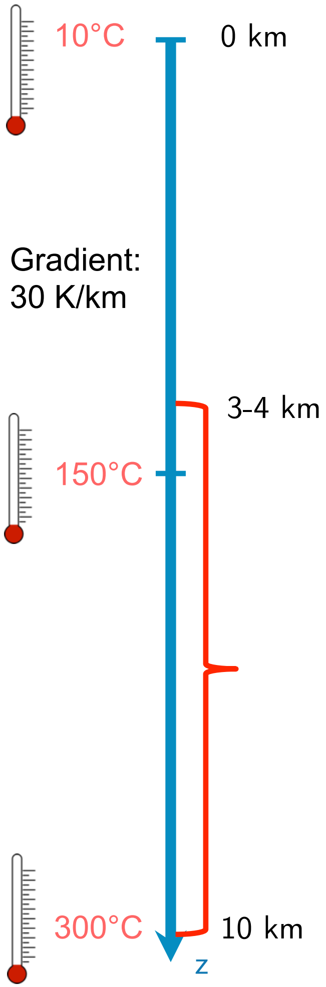


Geothermal power plants

Geothermal power plants

Using the heat above the ground

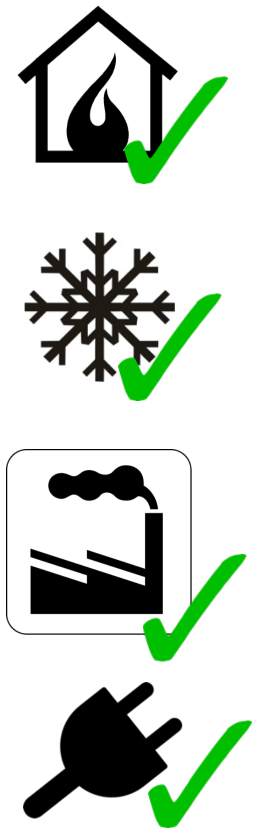
The focus of this part is only on the energy conversion cycles for production of electricty and cogeneration



Electricity production & cogeneration

- "High-enthalpy" applications
- Use of geothermal heat in energy conversion cycles for electricity and heat production (cogeneration)
- Compatible resources: hydrothermal, deep hydrothermal, Hot Dry Rock
- Keep in mind: there is always the option of using the heat directly (e.g. high T industrial processes, high T district heating)

End-uses



Sources:
[1] Minder et al. Energy conversion processes for the use of geothermal heat. Swiss Federal Office of Energy, 2007
[2] L. Gerber, Energy Conversion lecture notes – Geothermal Energy, 2009.

T_{ext} = extraction temperature
T_{in} = reinjection temperature

Heat available from the resource

$$\dot{Q}^+_{geo} = \dot{m} c_p (T_{ext} - T_{in})$$

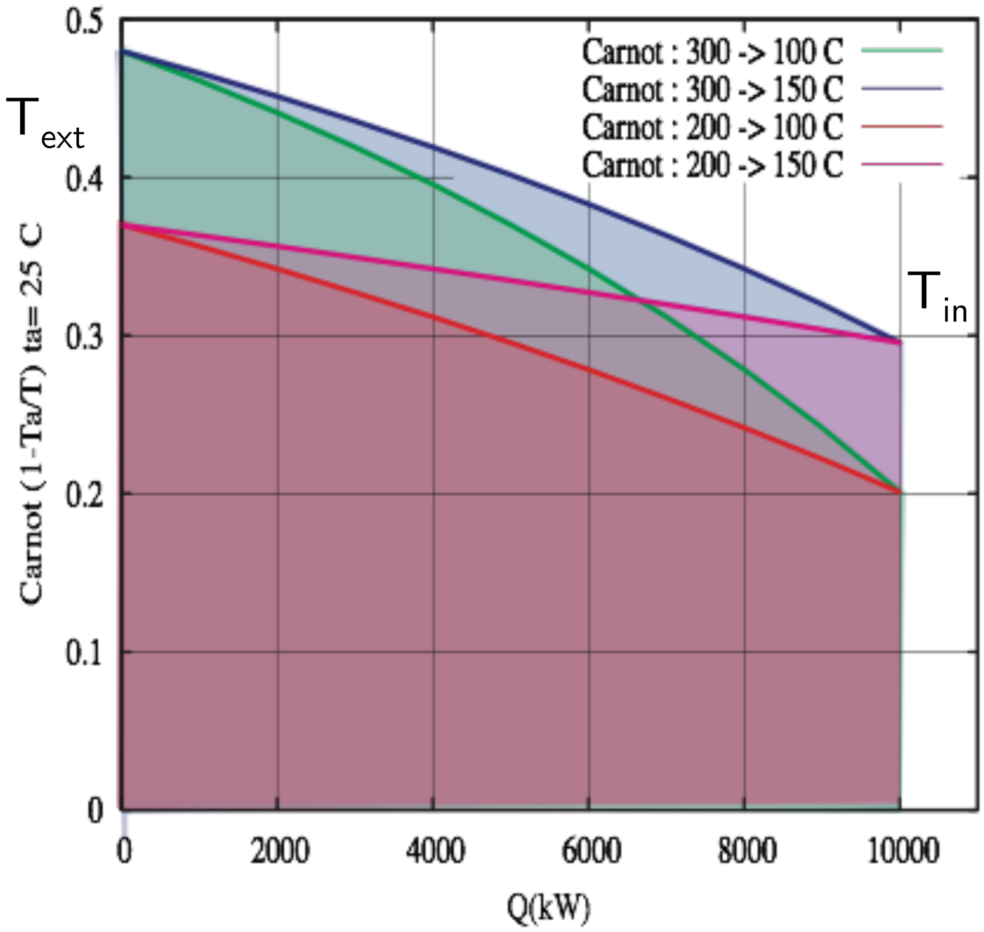
I-law efficiency (low!)

$$\varepsilon = \frac{\dot{E}^-}{\dot{Q}^+_{geo}}$$

Carnot factor and II-law efficiency

$$\theta_c = 1 - \frac{T_0}{T_{lm}} = 1 - \frac{T_0}{\frac{T_{ext} - T_{in}}{ln(\frac{T_{ext}}{T_{in}})}}$$

$$\eta = \frac{\dot{E}^-}{\dot{Q}^+_{geo} \theta_c}$$



Geothermal power plants

Sources:
[1] L. Gerber, Energy Conversion lecture notes – Geothermal Energy, 2009.

Cogeneration

T_{ext} = extraction temperature
T_{in} = reinjection temperature

Heat available from the resource

$$\dot{Q}^+_{geo} = \dot{m}c_p(T_{ext} - T_{in})$$

I-law efficiency (low!)

$$\varepsilon = \frac{\dot{E}^-}{\dot{Q}^+_{geo}}$$

Carnot factor and II-law efficiency

$$\theta_c = 1 - \frac{T_0}{T_{lm}} = 1 - \frac{T_0}{\frac{T_{ext}-T_{in}}{ln(\frac{T_{ext}}{T_{in}})}}$$

$$\eta = \frac{\dot{E}^-}{\dot{Q}^+_{geo}\theta_c}$$

With cogeneration Q_{DH} is produced for a District Heating network. The formulas become:

I-law efficiency (with cogeneration)

$$\varepsilon = \frac{\dot{E}^- + \dot{Q}^-_{DH}}{\dot{Q}^+_{geo}}$$

II-law efficiency (with cogeneration)

$$\eta = \frac{\dot{E}^- + \dot{Q}^-_{DH}\theta_{c,DH}}{\dot{Q}^+_{geo}\theta_c}$$

Sources:
[1] L. Gerber, Energy Conversion lecture notes – Geothermal Energy, 2009.
[2] R. Dipippo, Geothermal power plants, 2012

Classification

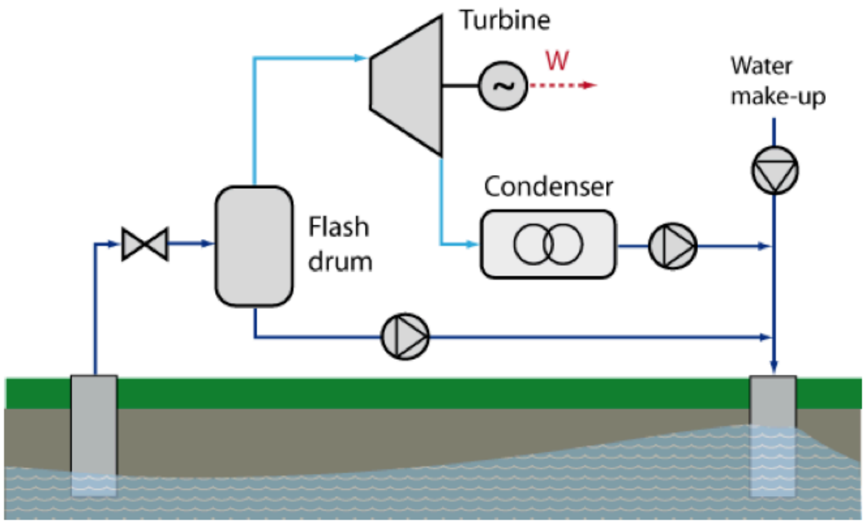
Different types of existing energy conversion cycles based on the working fluid:

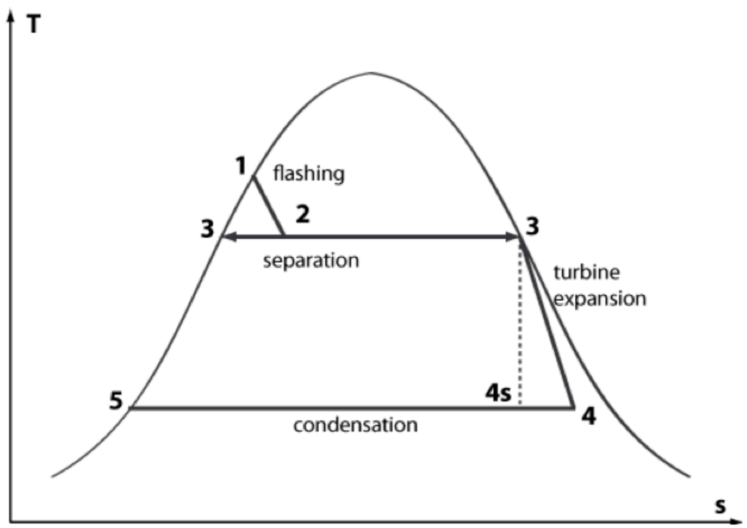
- Dry-steam power plants: oldest/simplest configuration → dry geothermal steam directly expanded in the turbine (rare case). 27% of worldwide installed capacity.
- Flash steam power plants (single/double): in liquid-dominated resources, flashing is done in order to separate vapor and liquid phases. With respect to worldwide installed capacity: 1-Flash 43%, 2-Flash 17%.
- Binary cycles (ORC/Kalina): if impossible to use a flash system due to low temperatures or quality of the geothermal fluid. Use of a secondary working fluid for the cycle, which exchanges with the geothermal fluid. Small plants, 40% of installed units, but only 6.6% of installed power.
- Other: combined and hybrid power plants

Sources:
[1] L. Gerber, Energy Conversion lecture notes – Geothermal Energy, 2009.
[2] R. Dipippo, Geothermal power plants, 2012

Single-flash steam power plants

- Liquid-dominated resource: need for separating liquid from steam (flashing)
- Water make-up to compensate for fluid losses
- Usually economically interesting if T > 150°C
- Optimization of flash drum pressure: higher pressure → higher specific power output, but lower steam flow rate
- Presence of chemicals and gases in the fluid: need of cleaning and gas removal
- Can be used for cogeneration

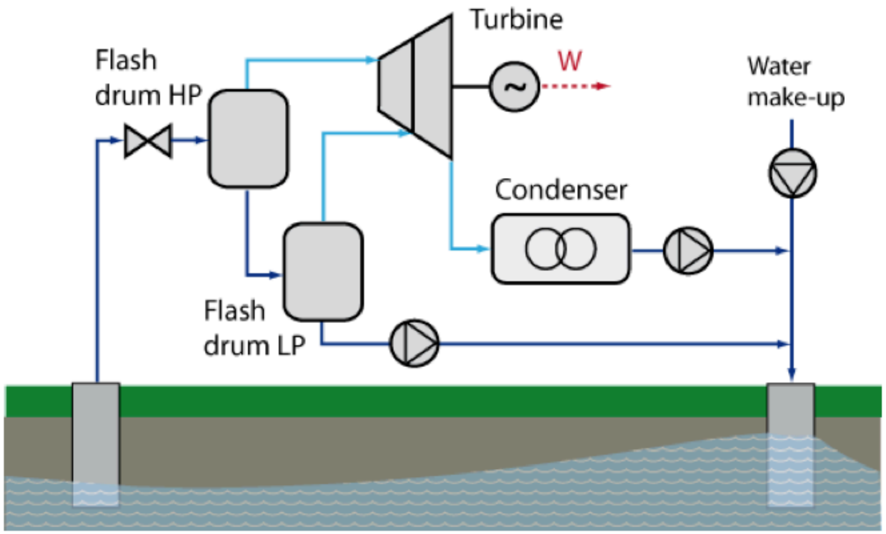


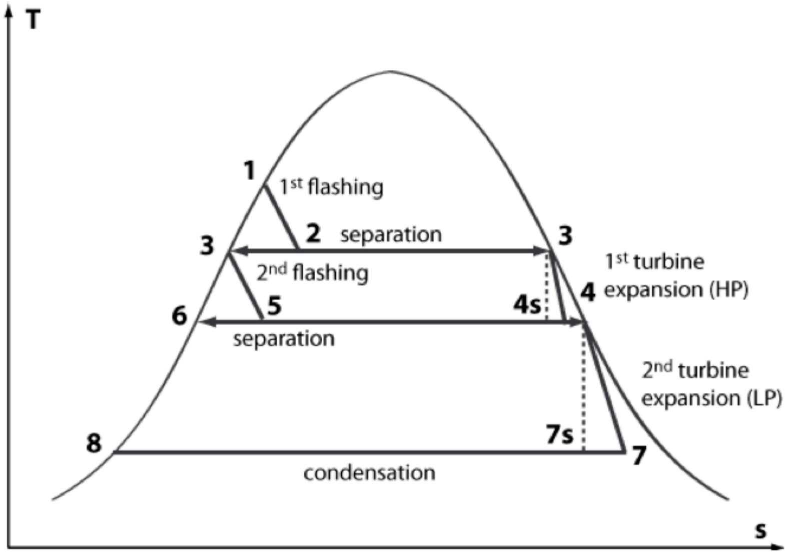


Sources:
[1] L. Gerber, Energy Conversion lecture notes – Geothermal Energy, 2009.
[2] R. Dipippo, Geothermal power plants, 2012

Double-flash steam power plants

- Evolution of the single-flash power plant → +15-25% power output
- Second flash drum at lower pressure increases the quantity of steam
- More complex design/optimization
- Additional flashing stages can be added (rare)
- Same technical issues as single-flash plants
- Can be used for cogeneration

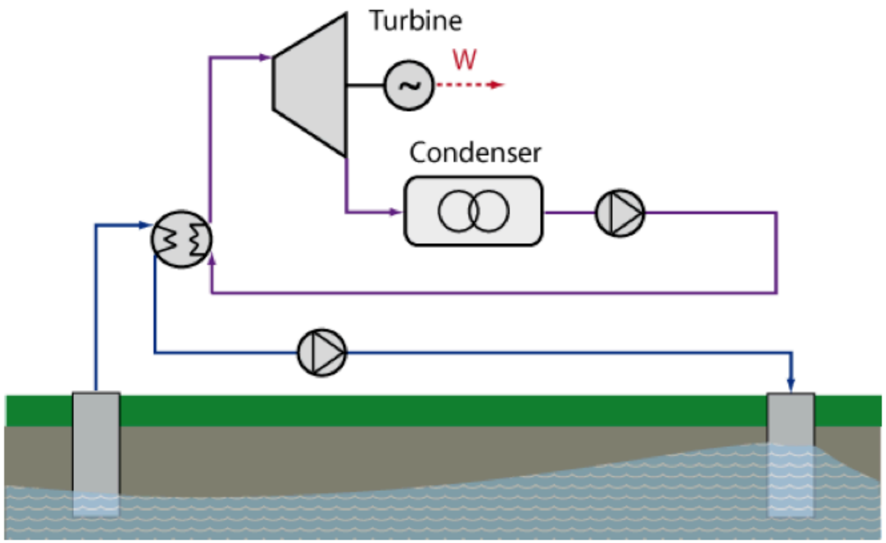


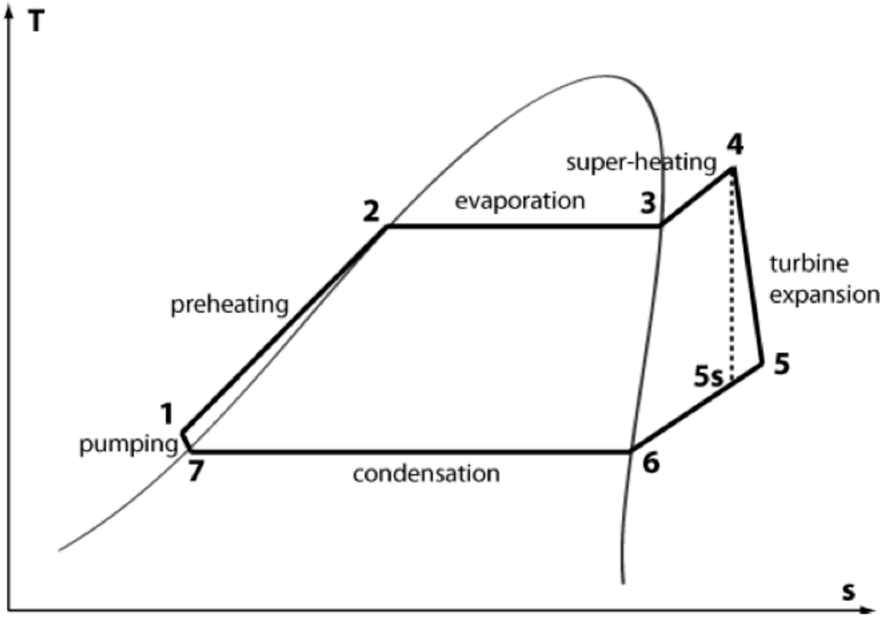


Sources:
[1] L. Gerber, Energy Conversion lecture notes – Geothermal Energy, 2009.
[2] R. Dipippo, Geothermal power plants, 2012

Binary power plants - ORCs

- Lower T applications → flashing difficult or non-economical
- Usually small scale (3MW_e/unit)
- Binary → use of an organic working fluid exchanging with geothermal water
- Can feature recuperator to increase efficiency
- Easier maintenance compared to flash systems
- No need for water make-up
- Condensation above atmospheric pressure → no risk of air inlet





Sources:
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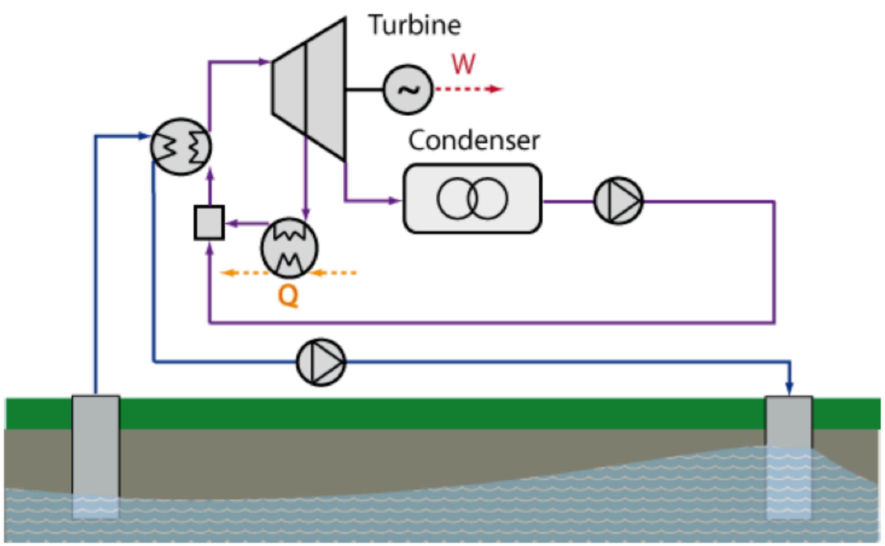
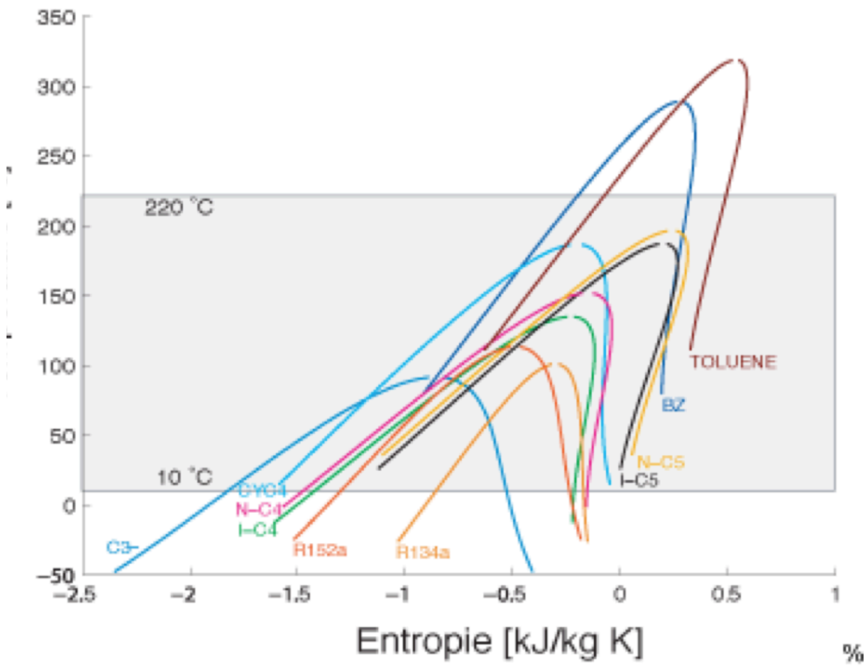
[2] R. Dipippo, Geothermal power plants, 2012

Binary power plants - ORCs

- Selection of working fluids: thermodynamic properties of the potential working fluids (e.g. critical temperatures and pressures, molar weight,...) but also the shape of the saturation curve
- Safety → organic fluids are flammable
- Cogeneration possible both for high and low temperature district heating networks



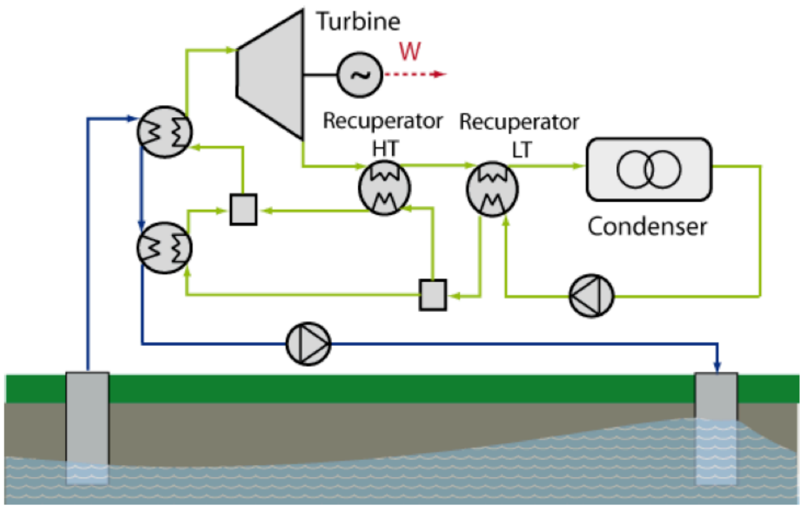


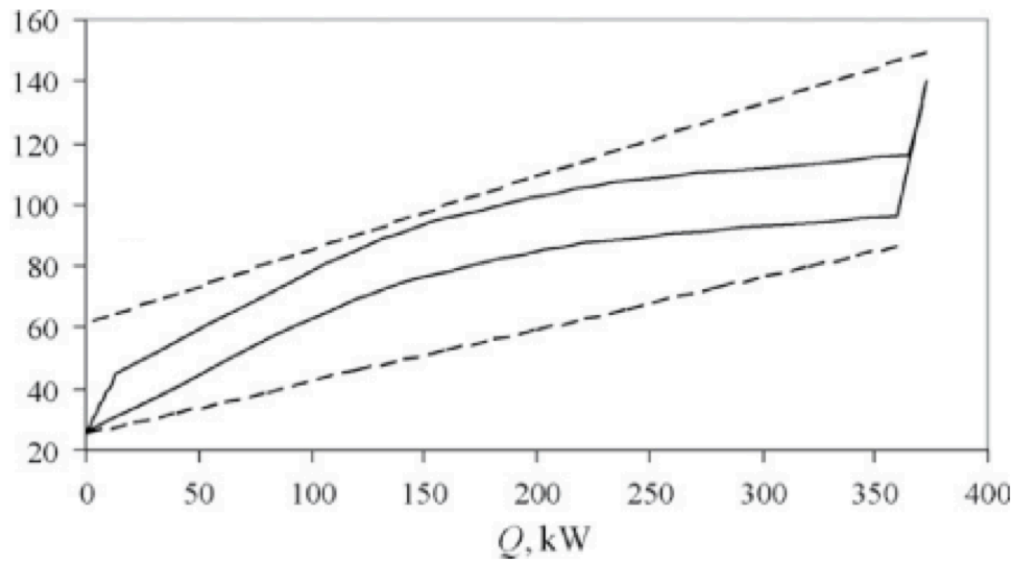
Geothermal power plants

Sources:
[1] L. Gerber, Energy Conversion lecture notes – Geothermal Energy, 2009.
[2] R. Dipippo, Geothermal power plants, 2012

Binary power plants – Kalina cycles

- Working fluid: mixture H_2O/NH_3: + non-inflammable, + well-known, - toxicity of ammonia
- Theoretical efficiency 30% higher than ORCs: mixtures of fluids do not change phase at constant temperature pressures → less exergy losses
- Key parameters: pressures, splitting factors, NH_3 concentration
- Can be used for cogeneration
- Different design based on resource T levels (e.g. KCS11 T > 120°C)

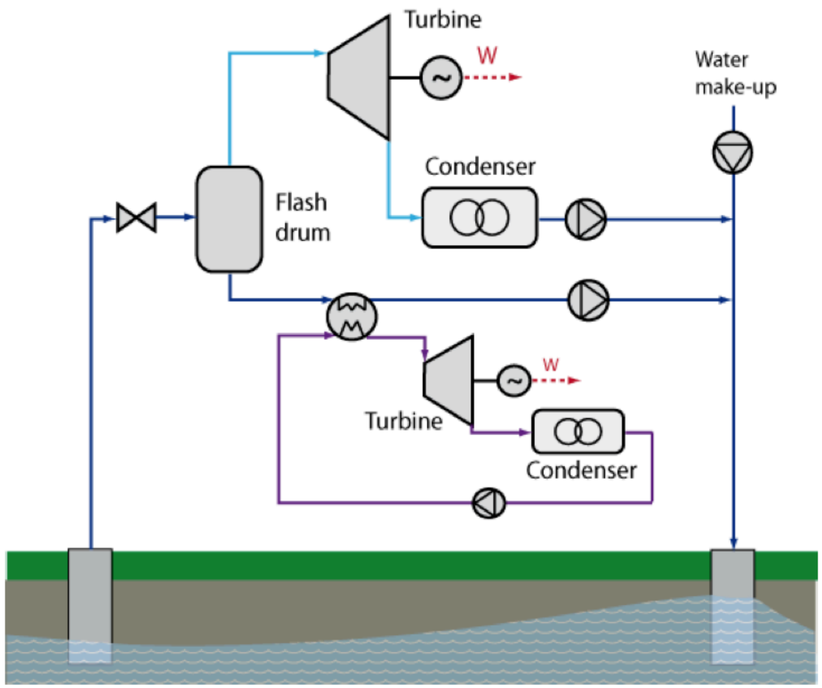


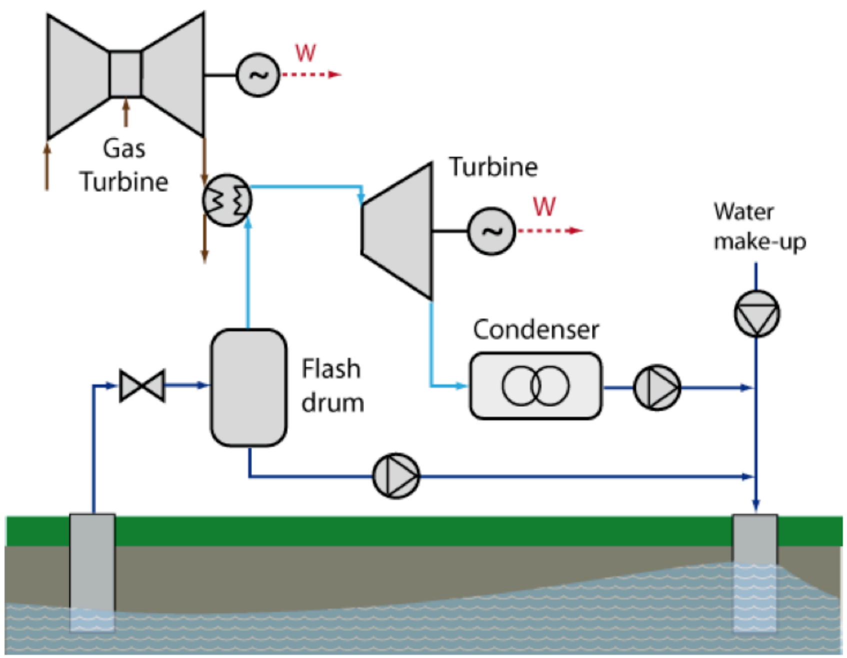


Sources:
[1] L. Gerber, Energy Conversion lecture notes – Geothermal Energy, 2009.
[2] R. Dipippo, Geothermal power plants, 2012

Other cycles

- Flash-binary cycles: combination of the two types of cycles to increase efficiency. More complex systems -> higher investment costs
- Hybrid cycles: combination with other resources. Geothermal heat can be used for pre-heating in a conventional power plants, or exhaust gases from a conventional power plant can provide superheating in geothermal plants





Geothermal power plants

Sources:
[1] L. Gerber, Energy Conversion lecture notes – Geothermal Energy, 2009.
[2] S. Hirschberg et al., Energy from the Earth, 2015

Thermo-economic performance

- Cost data (in red updated values from [2]):

	Flash	ORC	Kalina
Size range in MW_e	10 - 300	0.1 - 50	0.1 - 15
Plant life time yr	30	30	30
Production Temperature range in °C	180 - 350	100 - 240	120 - 200
Energy efficiency in %	10 - 20	6 - 16	n.a.
Exergy efficiency in %	< 75	< 50	n.a.
Investment costs in $/kW	2000 - 4000	2500 - 5500	3000 - 6000
O&M costs $/MWh	6 - 14	8 - 20	n.a.
(Without well) Levelized cost of electricity in $/kWh	0.02 – 0.03	0.04 - 0.07	n.a.

	Guanacaste	Beowawe	Svartsengi	Husavik
Type	Single-flash	Double-flash	ORC	Kalina
Fluid	geo. steam	geo. steam	isopentane	82%NH3/18%H2O
Size [MW]	55	16.7	1	2
Source T [C]	230	215	103	121
Exergy eff.	29.5%	46.7%	35%	45%
Cost [$/kW]	n.a.	1900	2400	975
Op. pres. [bar]	6	4.21/0.93	6.2	38.8
Cond. pres. [bar]	0.123	0.044	n.a.	5.4
Year	1994	1985	n.a.	2000
Country	Costa Rica	USA	Iceland	Iceland

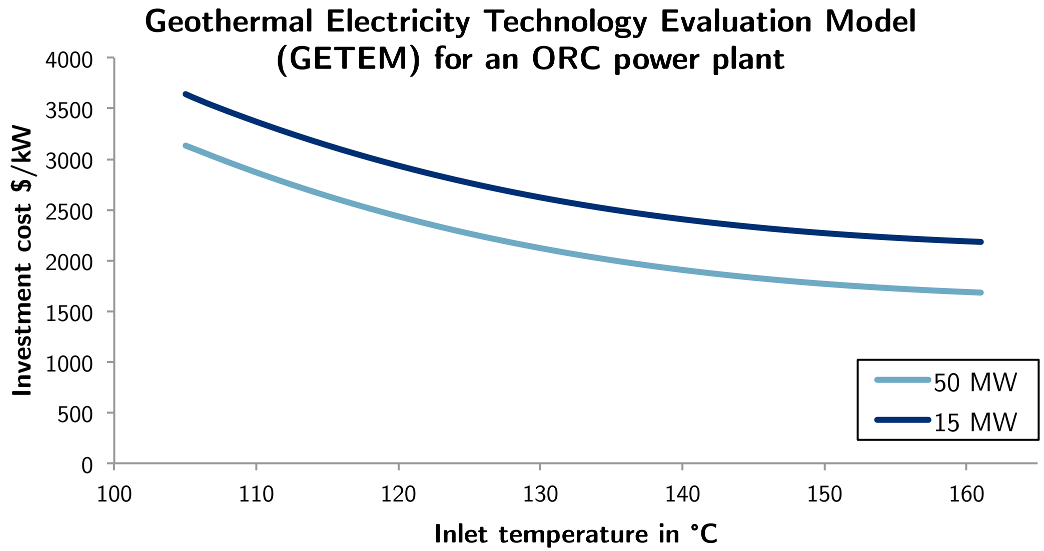
Geothermal power plants

Thermo-economic performance

Sources:
[1] K. F. Beckers et al., Levelized Costs of Electricity and Direct-Use Heat from Enhanced Geothermal Systems, 2013
[2] S. Hirschberg et al., Energy from the Earth, 2015
[3] http://www1.eere.energy.gov/geothermal/pdfs/getem_vol_iii_technical_appendixes.pdf

Performance and costs dependent of:

- Temperatures (T_{ext}, T_{in})
- Turbine inlet conditions (T, p) and size
- Pressure drop
- Type of working fluid
- …



Geothermal power plants

Sources:
[1] IEA, Technology Roadmap - Geothermal Heat and Power, 2011 (p. 18)

Thermo-economic performance

Figure 6: Production costs of geothermal electricity (USD/MWh$_e$)

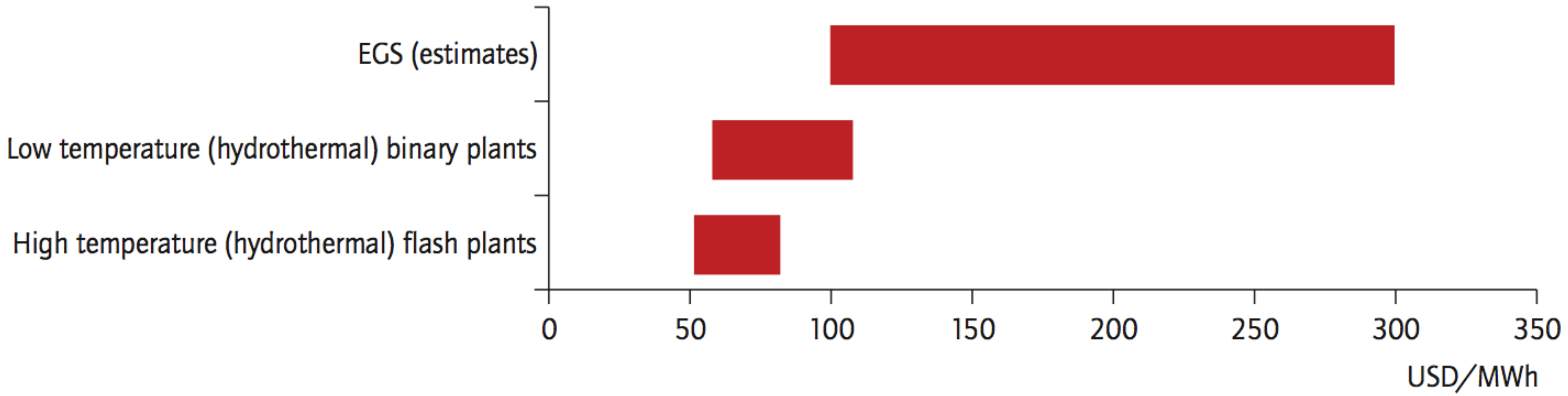
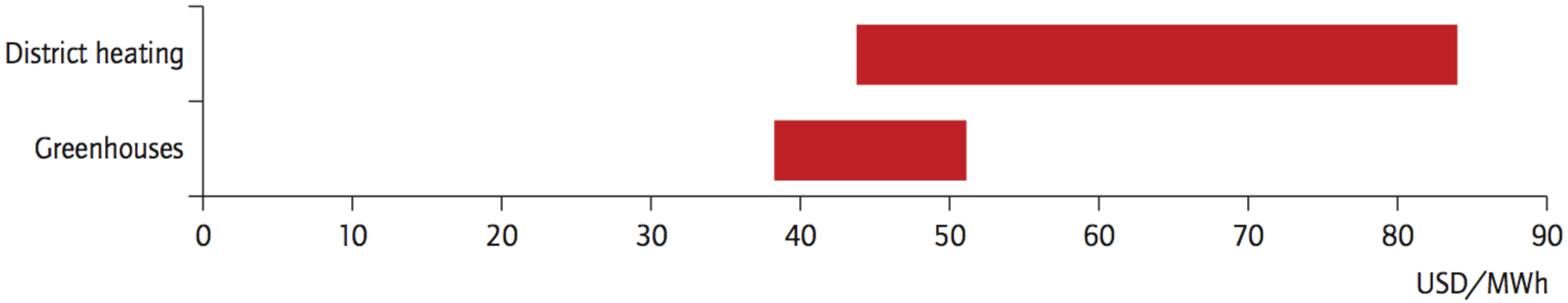


Figure 7: Production costs of geothermal heat use (USD/MWh$_t$)



Take-home message

Take-home message

- **Geothermal energy applications**
  - Based on its temperature, heat has different "value" and possible applications → system view is needed
  - Not only electricity! Ground Source Heat Pumps and direct use of heat can be viable alternatives to fossil fuels
  - Baseload: non-seasonal resource with high capacity factor
- **Resources**
  - Moving from location-specific to ubiquitous resources (EGS)
  - Huge potential (but technical difficulties → we didn't talk about seismicity for examples)
- **Geothermal power plants**
  - Low first law efficiencies, good exergy efficiencies
  - Most cycles can be used in cogeneration

Thank you! Questions?

Stefano Moret
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References

Most of the lecture material is taken from these sources:

[1] S. Hirschberg et al., Energy from the Earth, 2015
[2] IEA, Technology Roadmap - Geothermal Heat and Power, 2011
[3] R. Dipippo, Geothermal power plants, 2012
[4] IPCC, Special Report on Renewable Energy Sources and Climate Change Mitigation, 2011
[5] L. Gerber, Energy Conversion lecture notes – Geothermal Energy, 2009 (available on moodle)