

Deep geothermal energy – an introduction

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1 Introduction

A huge amount of thermal energy is stored within the earth. This energy was partially generated during the formation of the earth, but is also permanently generated due to radioactive decay and thermal convection in the upper mantle. Fig. 1.1 and 1.2 illustrate the temperature distribution inside the earth. The average temperature gradient in the crust is about $30^{\circ}\text{C}/\text{km}$, locally it can be much higher. The average heat flow in the crust is between 50 and $100 \text{ mW}/\text{m}^2$.

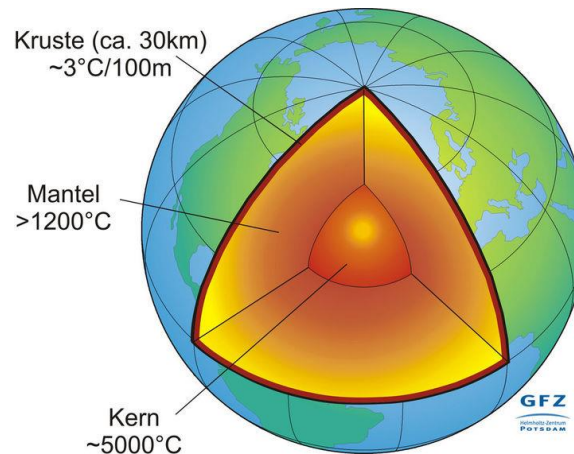


Fig. 1.1: Structure of the earth with temperature distribution (GFZ Potsdam)

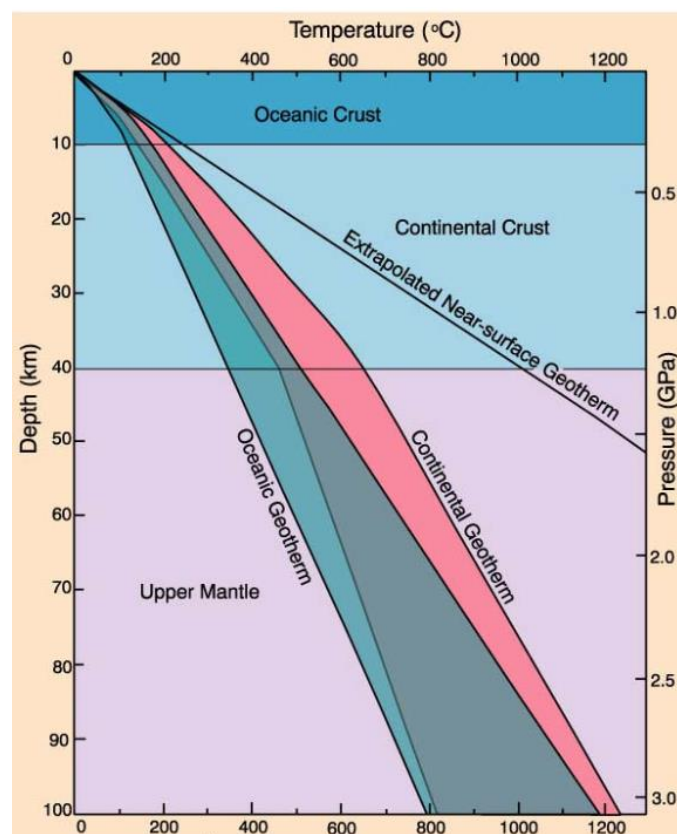


Fig. 1.2: Temperature and pressure – depth profiles

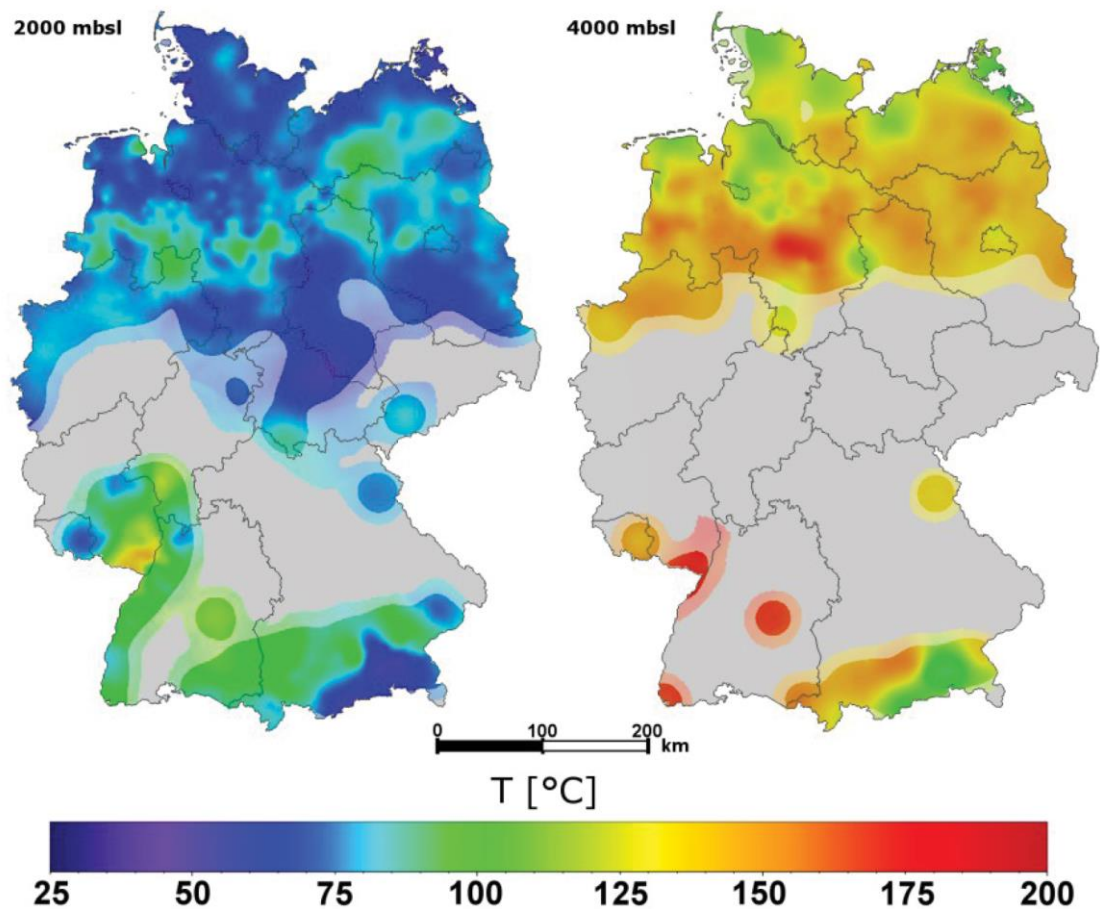


Fig. 1.3: Map of subsurface temperature in Germany: left 2000 m below surface, right: 4000 m below surface (Agemar, T. et al., 2014)

Fig. 1.3 shows the subsurface temperature distribution in Germany. The gray colour indicates regions where no reliable temperature data at depth are available.

Geothermal energy is used for the generation of electricity (about 50%) and for various thermal applications, including space heating and industrial heat input (REN21, 2020). Fig. 1.4 illustrates renewable shares of energy in relation to the total energy consumption worldwide and Fig. 1.5 shows geothermal power generation by countries. Both figures show the situation in 2017 and 2018, respectively. There is a clear trend for increase in renewable energies including an increasing use of geothermal energy.

If thermal energy is used for heating purposes, relatively low temperature may be sufficient, but for electricity production the temperature should exceed about 130 $^{\circ}\text{C}$ to be economical. A second criteria for an economic operation is a sufficient flow rate, which should exceed about 100 l/s.

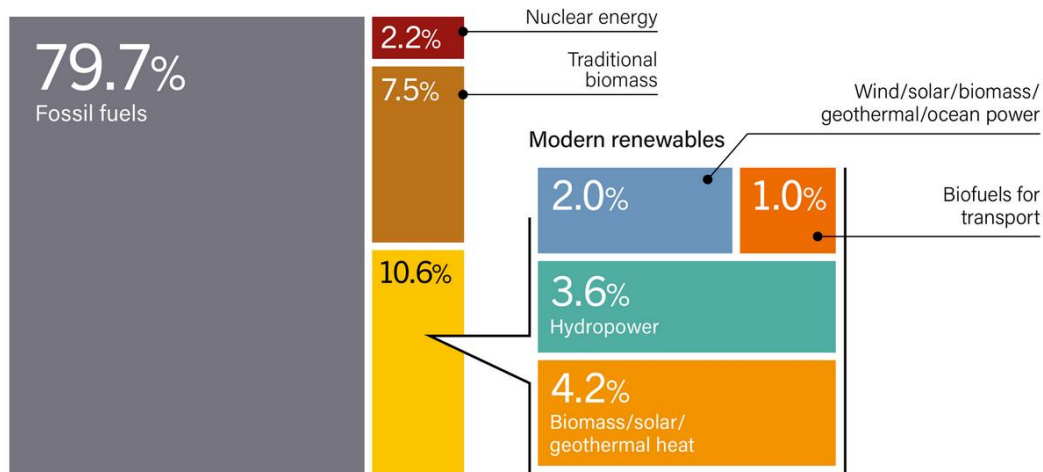


Fig. 1.4: Renewable share of total energy consumption 2017 worldwide (REN21, 2020)

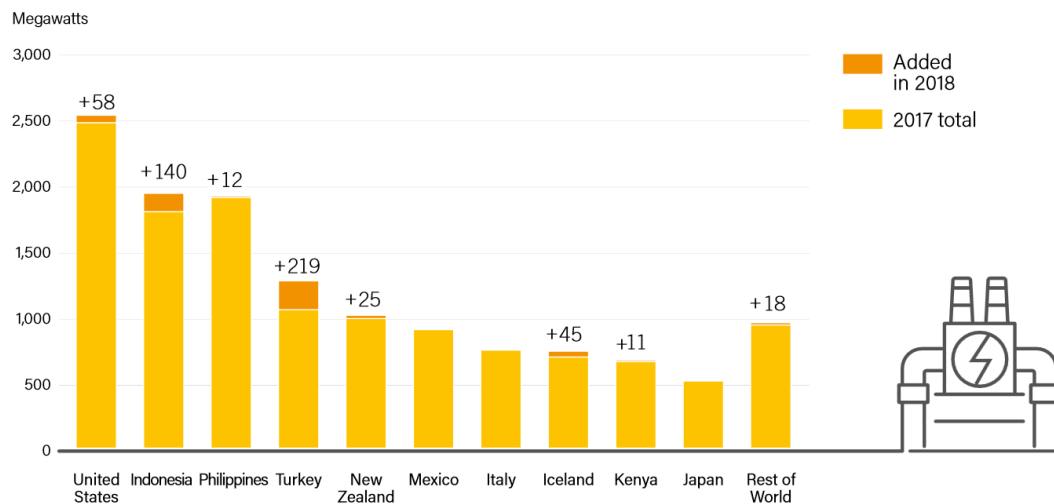


Fig. 1.5: Geothermal power capacity 2018 worldwide (REN21, 2020)

There are quite different possibilities to exploit geothermal energy like illustrated in Fig. 1.6. Deep geothermal energy considers reservoir (borehole) depths of more than 400 m and temperatures exceeding 20 °C.

According to enthalpy and existence of groundwater inside the reservoir deep geothermal projects can be classified as follows:

- Hydrothermal systems with low enthalpy (reservoir water temperature up to app. 100°C in aquifers or fault zones)
- Hydrothermal systems with high enthalpy
- Petrothermal systems (independent from water bearing systems, also called Hot-Dry-Rock (HDR) or Enhanced Geothermal Systems (EGS))
- Heat-exchangers in deep boreholes (either in water reservoirs or in HDR environment)

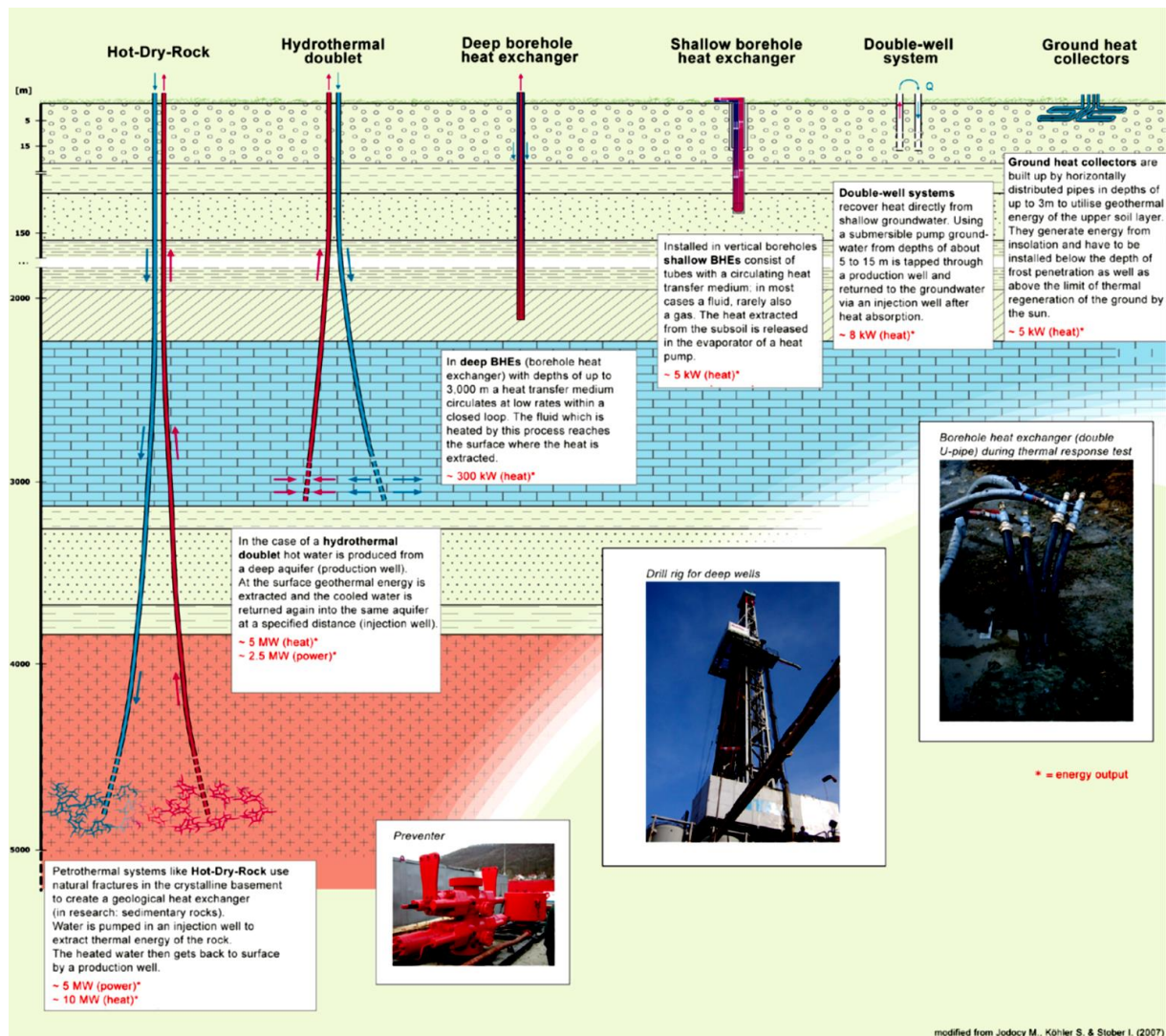


Fig. 1.5: Different types of geothermal systems (LIAG, 2017)

Compared to other (including renewable) energy resources, geothermal energy has the advantage that it is permanently available, has minimum land consumption and low environmental impact.

The development of deep geothermal projects is performed in several steps (see also Felix et al. (2010a,b)):

1. Preliminary survey (use of existing information, risk assessment, numerical modelling, environmental investigations, economical estimations etc.)
2. Exploration (geological, geophysical (especially 3D seismic), rockmechanical, hydraulic)
3. Well design (choice of drilling technique, logging techniques, borehole diameter, casing etc.)
4. Drilling of production and reinjection wells incl. well testing and logging
5. Reservoir development (stimulation)
6. Production and monitoring (heat and/or electricity production, well observation, temperature and pressure monitoring, chemical monitoring, seismic monitoring, ground movement monitoring etc.)

2 Hydrothermal systems

Hydrothermal systems (Fig. 2.1) use deep aquifers with high permeability. The idea is to reinject the water back into the same formation. This is of special importance in case of high degree of mineralization. This technology is already well developed and used worldwide, for instance in the molasses basin around Munich in Germany, see for instance Farquharson et al. (2016) or Przybycin et al. (2017). A general problem in hydrothermal systems is the mineralization or salinity of the aquifer water, which can cause corrosion of the equipment or blockages.

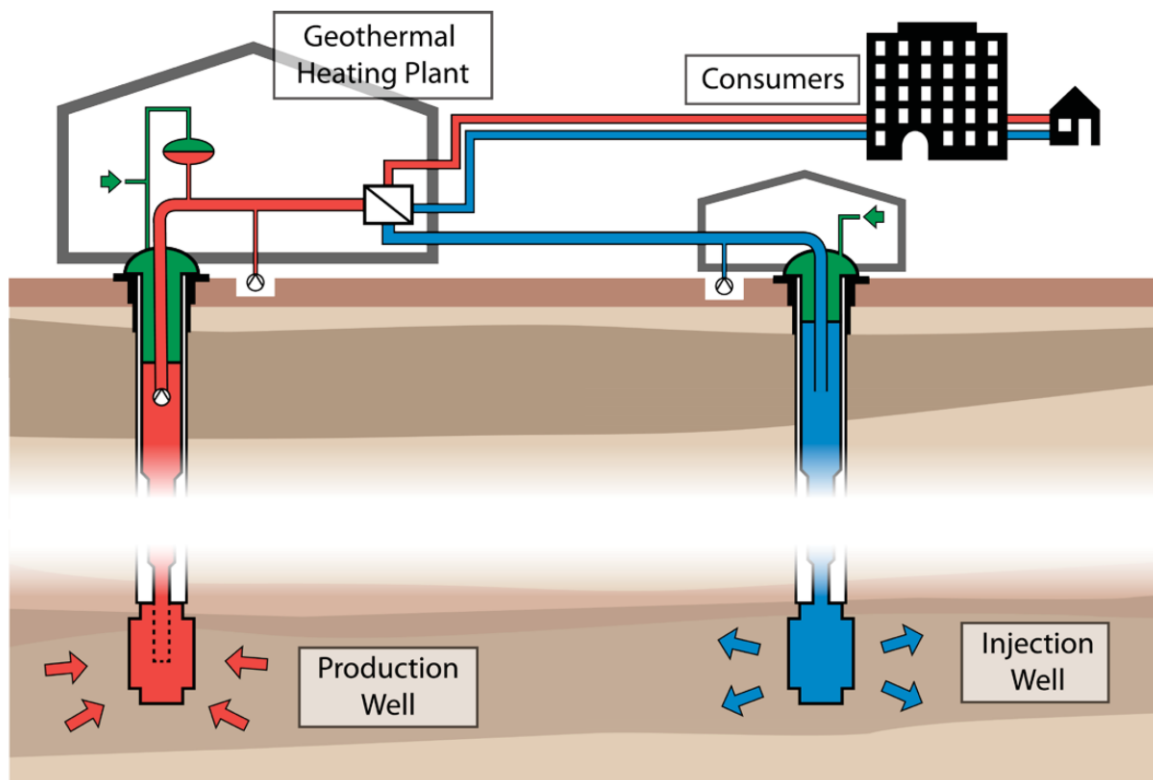


Fig. 2.1: Principle sketch of a hydrothermal system (LIAG, 2017)

3 Petrothermal systems

A typical petrothermal system (see Fig. 3.1) consists injection and production wells, observation wells, the heat exchanger and the power station at the surface with several components.

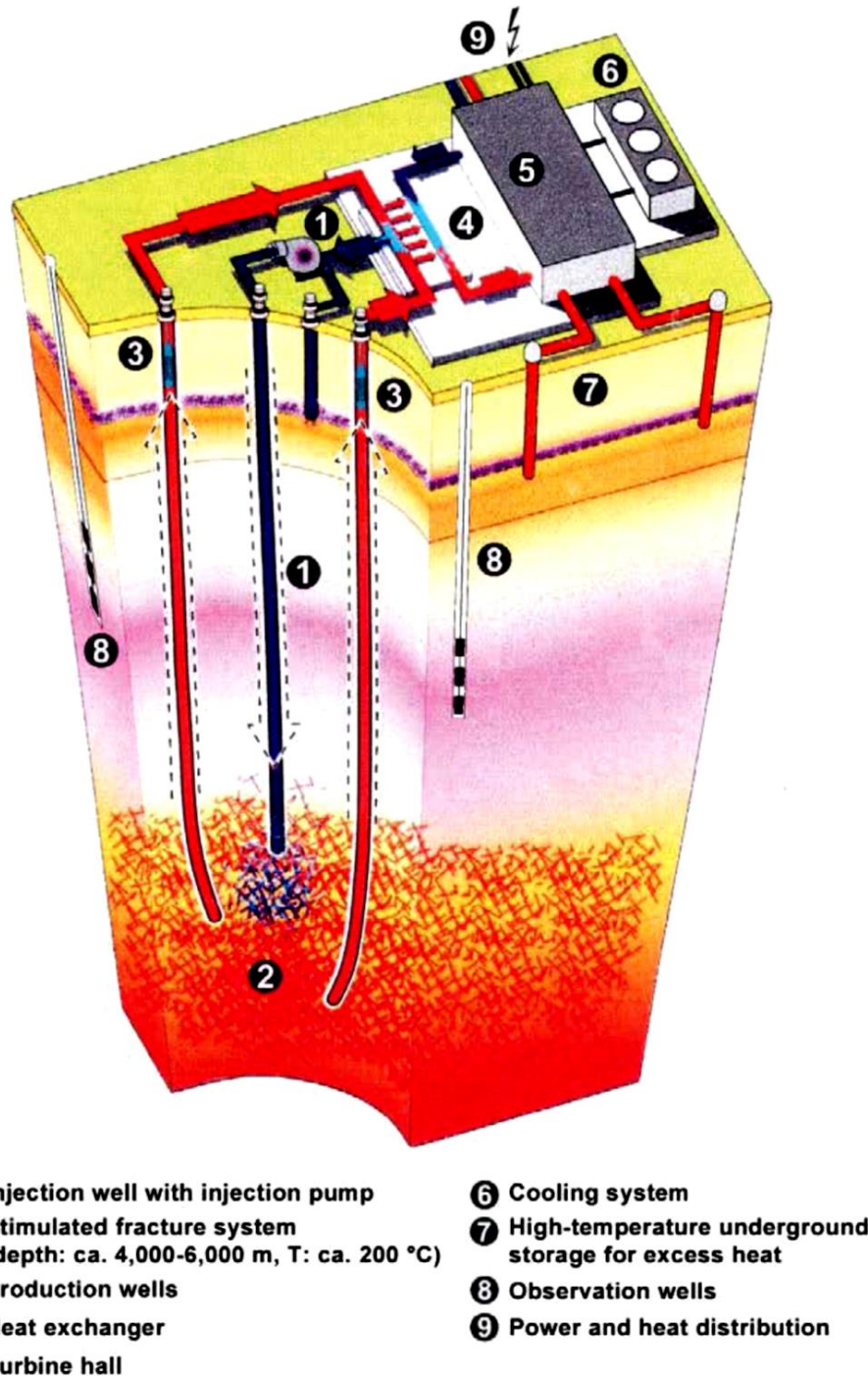


Fig. 3.1: Basic structure of a HDR system with its main components (LIAG, 2017)

The underground heat exchanger of petrothermal systems can be designed in different ways (see Fig. 3.2):

- Systematic man-made fracture system (engineered system)
- Network of fractures and cracks
- Interconnected large-scale fractures or faults

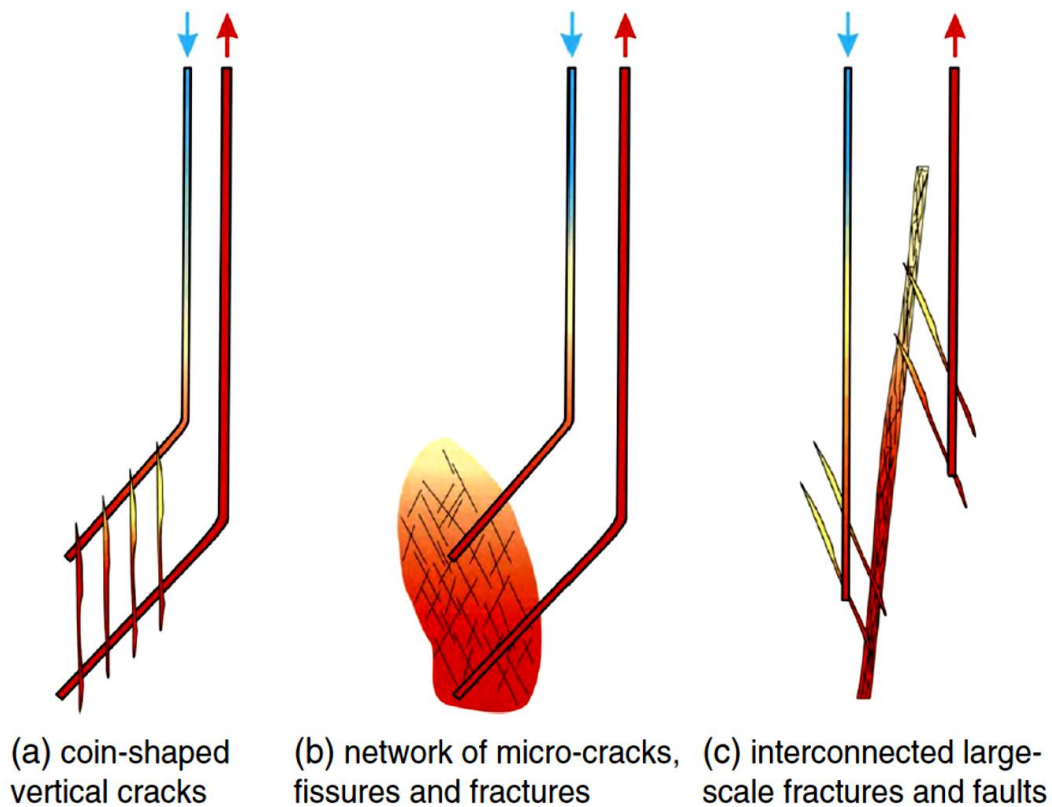


Fig. 3.2: Potential designs for underground heat exchanger for HDR systems (Jain et al., 2015)

Fig. 3.2 shows so-called doublets (two wells: injection well and production well). Another option is to use three boreholes (triplet) with either one injection and two production wells or vice versa (see also Fig. 3.1).

The use of existing faults or large-scale fractures has the advantage of higher permeability and good connectivity between injection and production well. On the other side such systems are susceptible to induced seismicity (reactivation of fault movement during stimulation or production).

4 Geothermal basics

The energy output from a geothermal system can be estimated by using Eq. 1.

$$E = Q \cdot \Delta T \cdot C_F \cdot \rho_F \quad (1)$$

where:

E	generated energy (output energy)
Q	flow rate
ρ_F	fluid density
C_F	specific heat capacity of fluid
ΔT	temperature difference between input and output in power plant

According to of Eq. 1 the key parameters which control the efficiency of a geothermal system are flowrate and temperature at the underground heat exchanger. The flowrate is mainly determined by the permeability of the underground heat exchanger (natural component), but also by the diameter of the well and pump capacity (technical components). Permeability (either matrix or joint permeability) can be enhanced by stimulation (see chapter 6).

The heat extraction from the underground leads to a cooling inside the underground heat exchanger, which determines the lifetime of the system. The faster the heat extraction the shorter the lifetime. After shut-down of a geothermal system, the underground heat exchange can recover completely after a few years.

The specific heat capacity of rocks is between 700 and 2500 J/(kg·K). The value for hard rocks is between 700 and 1300 J/(kg·K).

The recovery of the underground heat exchanger is dependent on the heat flux according to Eg. 2 and can be quite different.

$$q = \lambda \cdot \text{grad } T \quad (2)$$

where:

q	heat flux
λ	thermal conductivity
grad T	temperature gradient

The average thermal conductivity of the earth's crust is about 2 – 2.5 W/(m·K). However, for different types of rock it can vary between 1 and 6 W/(m·K). In general thermal conductivity is slightly going down with increasing temperature. Water has significant lower values depending on temperature (at room temperature the value is about 0.6 W/(m·K)).

Detailed analysis of the energy balance needs hydro-thermal coupled numerical simulations, to some extend also hydro-thermo-mechanical calculations because the permeability of the underground heat exchanger is a function of the stress state in the rock mass.

5 Electricity generation

Depending on reservoir temperature two systems can be used to produce electricity:

- Flash power plants (direct use of steam for turbine, requires geothermal temperature above about 180°C)
- Binary power systems (use of heat exchanger, requires geothermal temperature above 130 °C to be economical, but works in principle also with temperatures above 80 °C)

Binary power systems use either the Organic Rankine Cycle (ORC) or the Kalina cycle. Fig. 5.1 illustrates the different components of geothermal power plants and the application of the different systems worldwide in 2015.

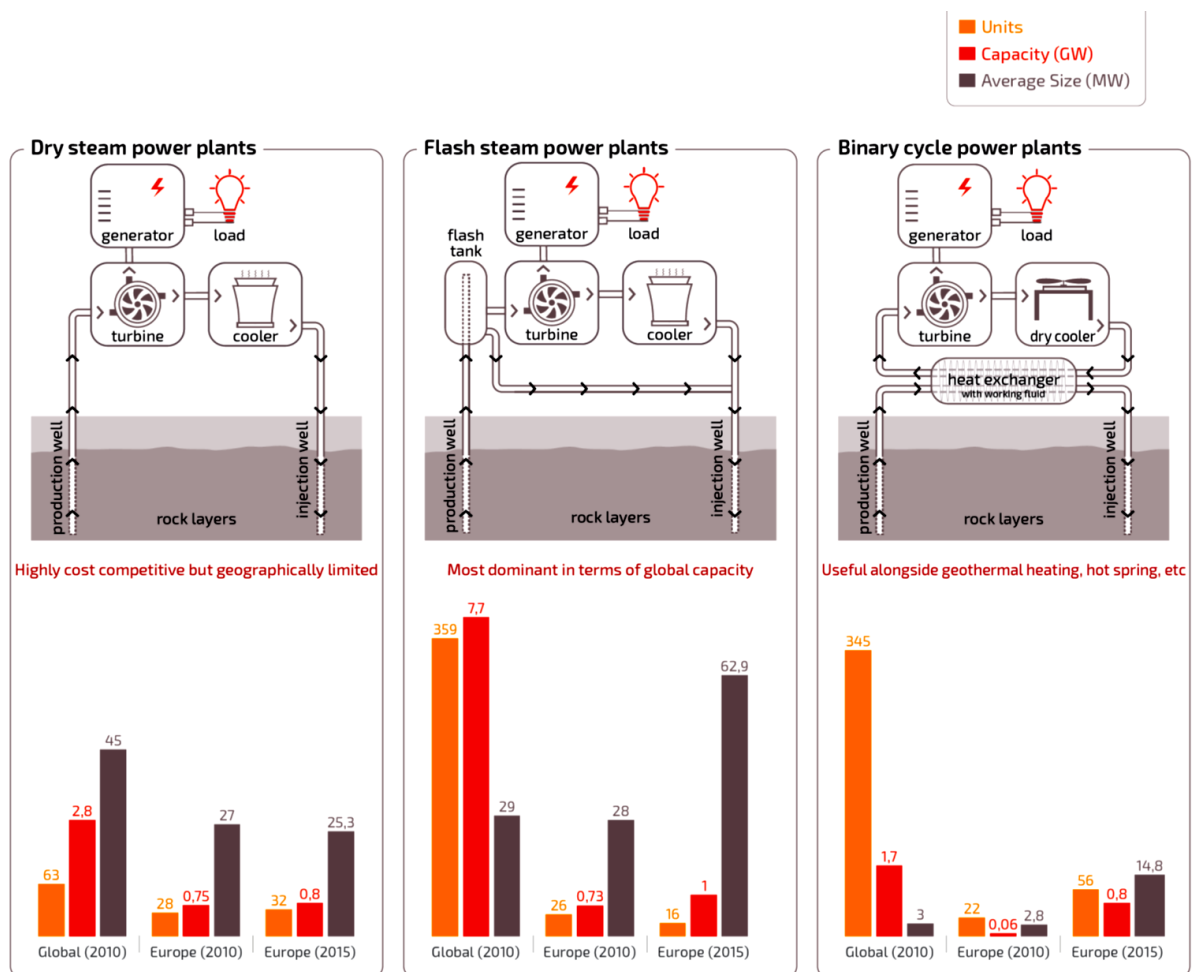


Fig. 5.1: Sketch of flash and binary power systems (EGEG, 2016)

Exemplary, Fig. 5.2 shows the geothermal power plant of the EGS Soultz with an ORC system with 1,5 MW electric energy output (Genter et al., 2009).



Fig. 5.2: The geothermal power plant EGS Soutz (Genter et al., 2009)

6 Stimulation

Globally, HDR (EGS) systems have by far the largest geothermal energy potential. On the other side, dry rock formations have often not the required permeability to reach a sufficient flow rate. Therefore, stimulation of the reservoir to enhance the permeability is necessary. The classical stimulation technique is hydraulic fracturing (other potential techniques are mentioned in chapter 7).

In principle two different hydraulic stimulation approaches are used:

- Stimulation of existing natural fracture/fault systems
- Creation of new parallel oriented fractures in an unfractured (virgin) rock volume

The first one enhances the permeability by widening and interconnecting existing structures. By adding proppants (like done in petroleum engineering) a permanent opening of the widened fracture network can be reached.

Fig. 6.1 illustrates the principle stimulation mechanisms:

- Pure tensile mode
- Pure shear mode
- Primary fracturing with shear-stimulation leak-off (PFSSL), which is a combination of new fracture opening and hydro-shearing of natural fractures
- Mixed-mechanism stimulation, which is start with tensile fracturing and propagates later with hydro-shearing along natural fractures

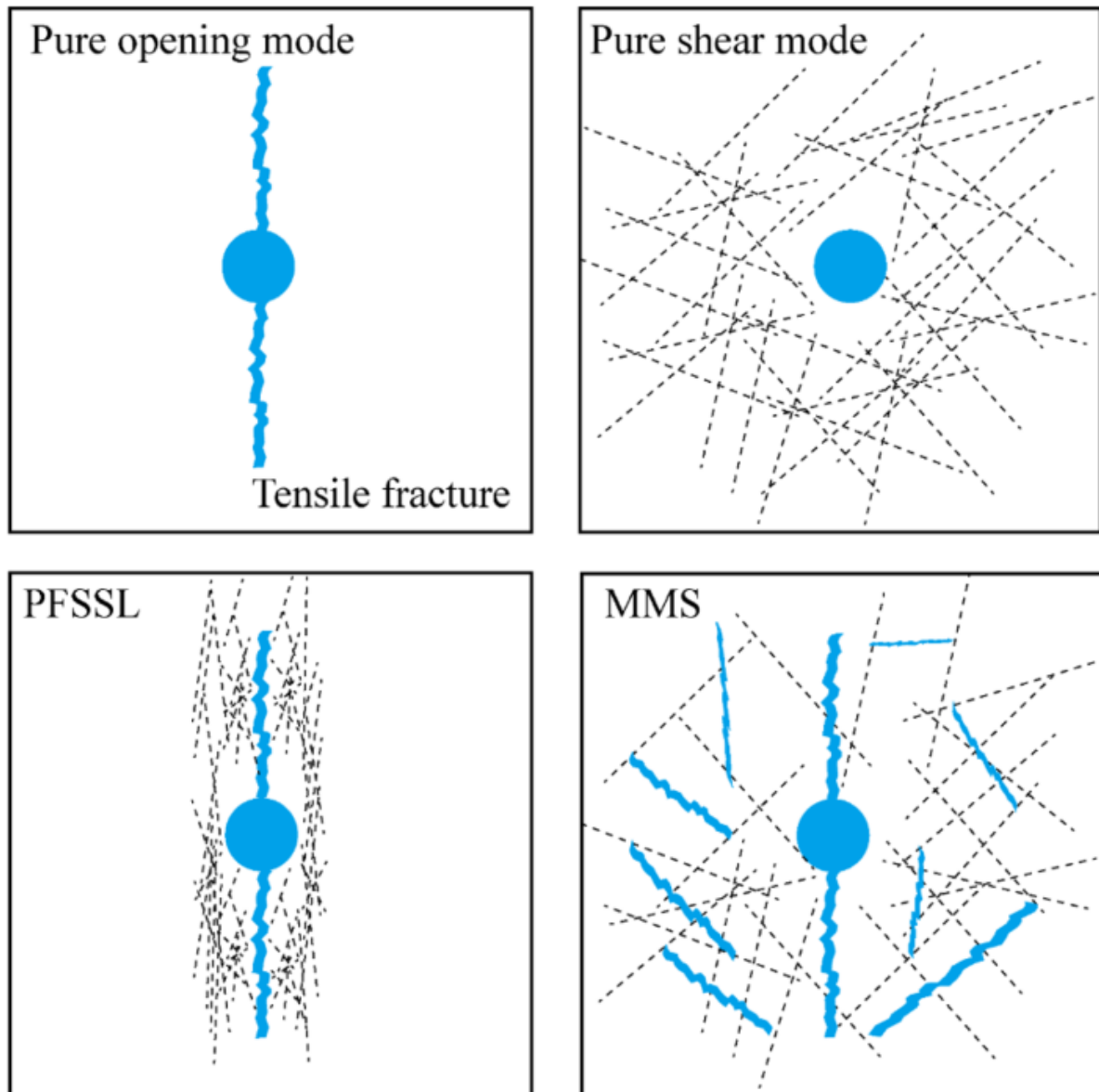


Fig. 6.1: Schematic presentation of potential hydraulic stimulations mechanisms (Jia et al, 2022)

Different injection schemes of hydraulic fracturing (see Fig. 6.2) can be applied to enhance the permeability of the underground heat exchanger. Different schemes can produce different flow path pattern, different level of permeability enhancement and have significant influence on induced seismicity.

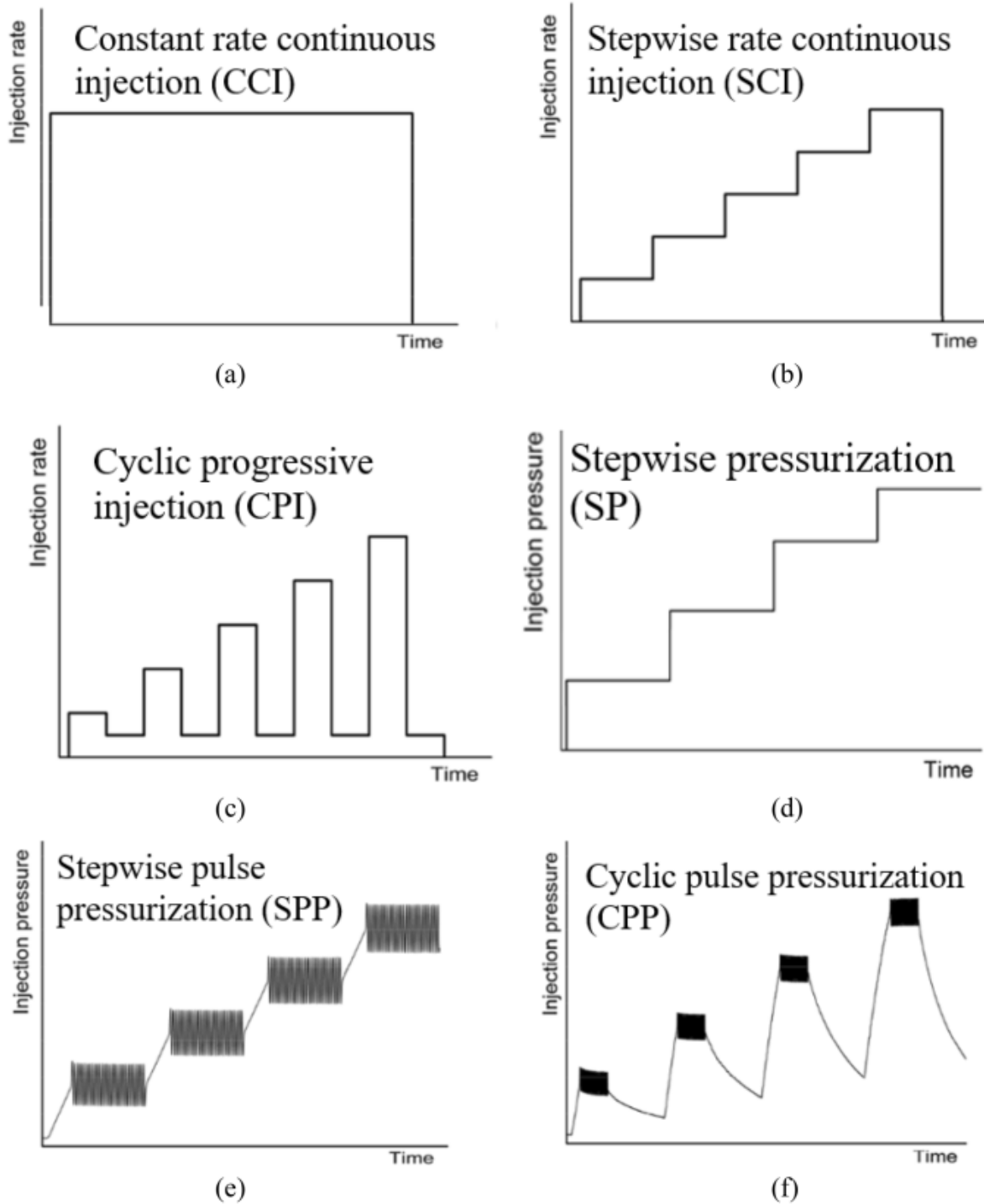


Fig. 6.2: Different injection schemes of hydraulic fracturing (Jia et al, 2022)

The general idea behind the second one – also called multi-fracture system - is the following: several parallel fractures are created, which are connected by injection and production wells (see Fig. 6.3).

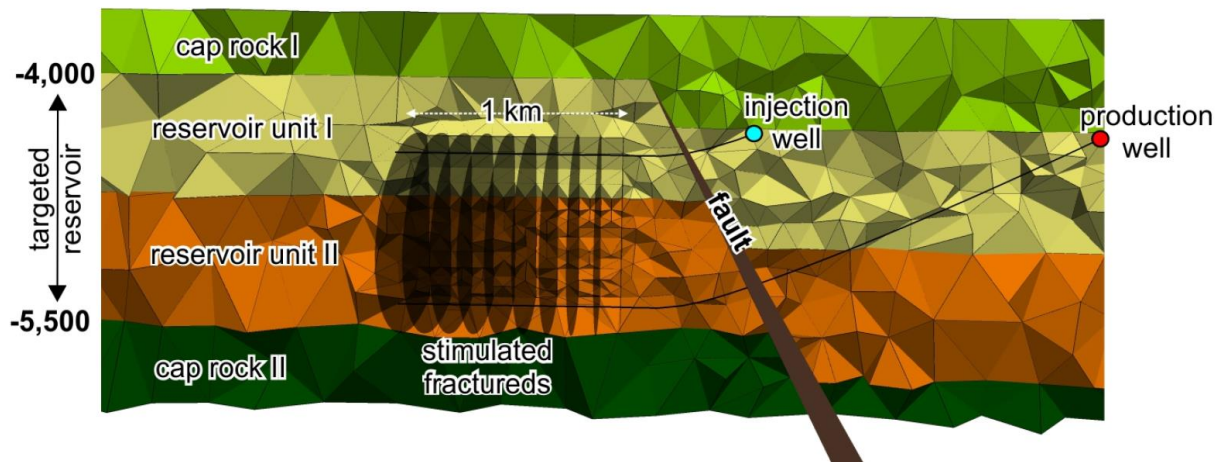


Fig. 6.3: Principle of multi-fracture system (Cacace & Jacquey, 2017)

Hydraulic stimulation is a complicated process, which depends on several factors:

- In-situ stress field
- Strength anisotropy
- Interaction with existing discontinuities (fractures, faults etc.)

Seismic monitoring is an excellent tool to observe the stimulation process (see Fig. 6.4). The stimulated volume as well as the activation of individual faults or fractures can be observed by location of observed acoustic events. This technique can also be used as instrument to manage (control) the production process.

Via numerical simulation the hydraulic driven fracture propagation can be predicted under consideration of complex geological-geomechanical conditions (e.g. Zeeb & Konietzky, 2015; Wasantha & Konietzky, 2016; Wasantha et al. 2017a,b). Exemplary, Fig. 6.5 shows the simulation result of a hydraulic driven multi-fracture system under consideration of optimum orientation to the in-situ stress field.

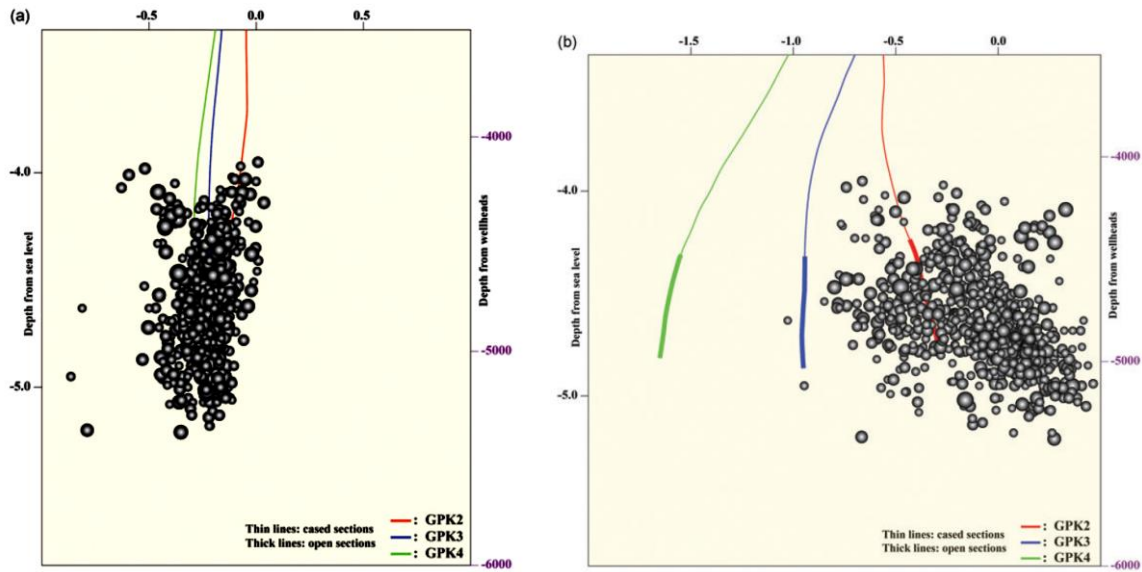


Fig. 6.4: Located seismic events during massive stimulation of well GPK2 at the geothermal site Soultz (Deborath, 2009)

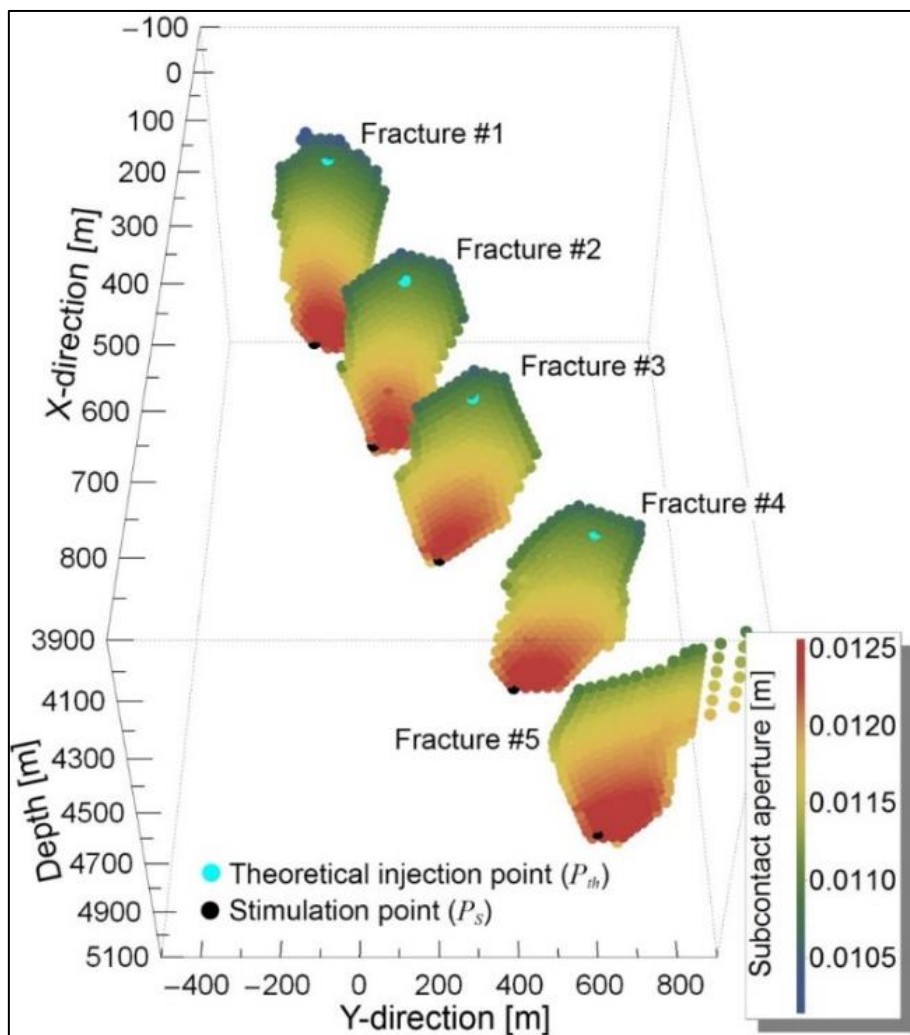


Fig. 6.5: Numerical simulation of a multi-fracture system with indication of fracture opening (Zeeb & Konietzky, 2015)

Numerical simulations, like documented by Zeeb & Konietzky (2015), Wasantha & Konietzky (2016) or Wasantha et al. (2017a,b) showed that:

- the in-situ stress field influences the fracture propagation direction
- stress barriers can stop the fracture propagation
- a stress shadow effect has to be considered for fractures close to one another
- orientation of injection and production boreholes have to be optimized in relation to the orientation of the principal stresses
- depending on fracture properties and pumping rate, hydraulic driven fractures can be cross existing fractures or deviated into the direction of the existing fractures

Hydraulic stimulation is performed by straddle-packer assemblies (two packers with injection interval in between), similar to those used in petroleum engineering. In case of extremely high temperature aluminum packer can be used.

7 Environmental impact

Geothermal energy is a renewable and in general environmental friendly energy source. Nevertheless, a few aspects of potential environmental impact have to be considered.

The most crucial potential impacts are:

- Induced seismicity
- Land subsidence
- Radiological pollution (in case the underground heat exchanger consists of radionuclide bearing rocks)

Potential impacts with lower significance are:

- chemical pollution of surface or groundwater by gaseous or aqueous components emitted by the geothermal system (plant and its components)
- Scales which are formed from geothermal fluids
- Noise

As documented by Heimlich et al. (2015) vertical and horizontal displacements up to about 5 cm were observed during different operation phases of the geothermal power plant in Landau (Germany).

Induced seismicity attracts most attention, although severe damage has not to be expected. According to Majer (2007, 2012), Deichmann et al. (2009), Bachmann et al. (2011) or MAGS (2013) the largest magnitude ever observed was about 3.5 and predictions suggest that this might be the maximum magnitude one has to expect for deep geothermal systems in general. Grünthal (2014) collected data from induced seismic events and natural earthquakes in Central Europe and compared them. Fig. 7.1 shows a comparison of different sources of seismicity and documents that geothermal projects produce comparably very low induced seismicity.

Latest research offers modified techniques to reduce the seismic risk by using cyclic stimulation techniques (e.g. Hofmann et al., 2018) or stimulation fluids with higher viscosity. Also, explosive, gas pulsed, thermal or laser-based stimulation techniques are under investigation and partially already used.

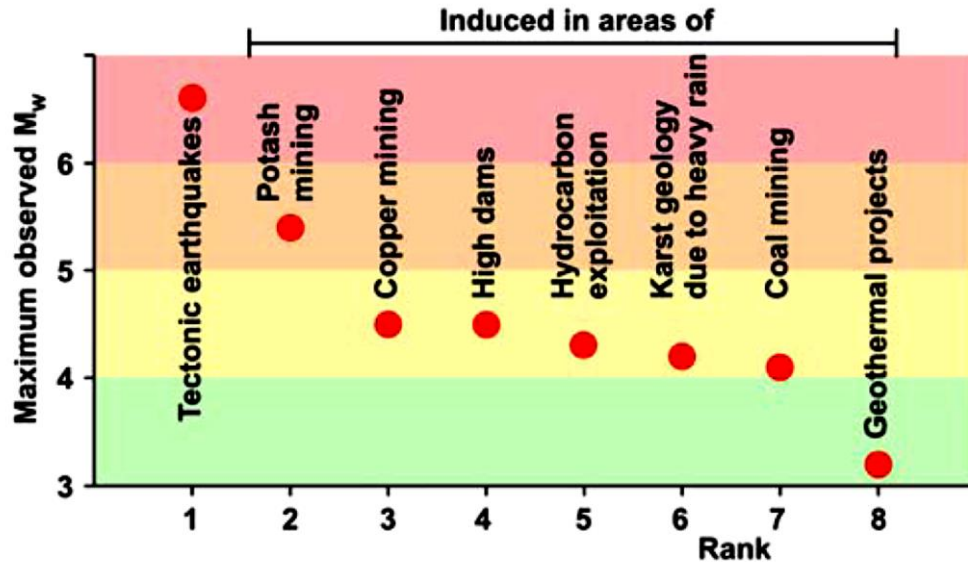


Fig. 7.1: Ranking of maximum observed magnitude for different sources of seismicity in Central Europe (Grünthal, 2014)

Exemplary, Fig. 7.2 documents observation results from the deep geothermal projects in Landau and Insheim (both are located in the Upper Rhine valley, Germany). The geothermal induced events are compared with induced seismicity caused by quarry blasting.

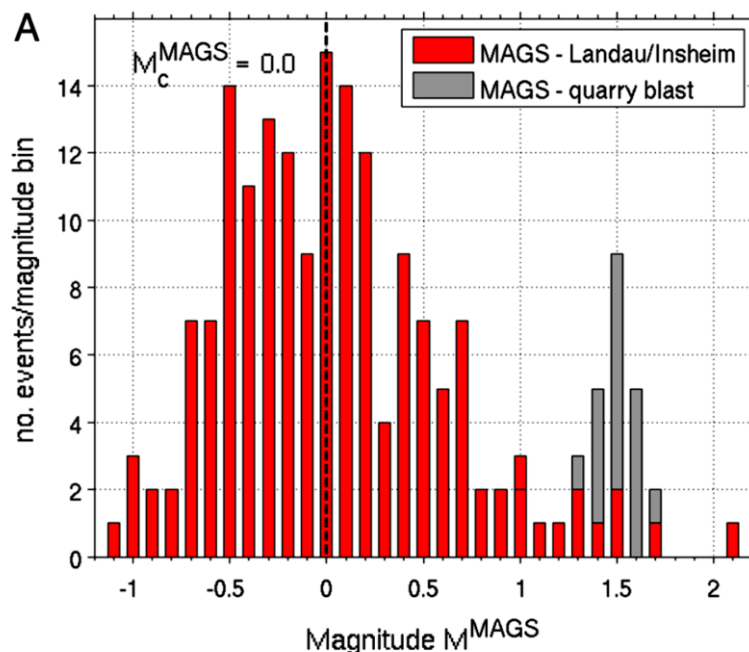


Fig. 7.2: Magnitude frequency distribution for events (geothermal induced and quarry blast) in Landau and Insheim, Germany, between October 2013 and September 2014 (Vasterling et al., 2017)

8 Geoenergy structures

Geothermal energy can also be used in combination with infrastructural buildings, like tunnels or foundations. The geothermal energy can be used directly or in an enhanced manner by using heat pumps. A few applications are already working successfully (see for instance Meibodi & Loveridge (2022), Barla & Insana (2025), Di Donna 2025, Aresti et al. (2024)) as heat exchange pipes integrated into tubbings, retaining walls, piles or tunnel linings. These systems can be used for heating or cooling. A few potential applications:

- Heating or cooling of underground railway stations or subway stations
- Heating or cooling of buildings at the surface
- Heating of tunnel portals
- De-icing of tunnels lanes

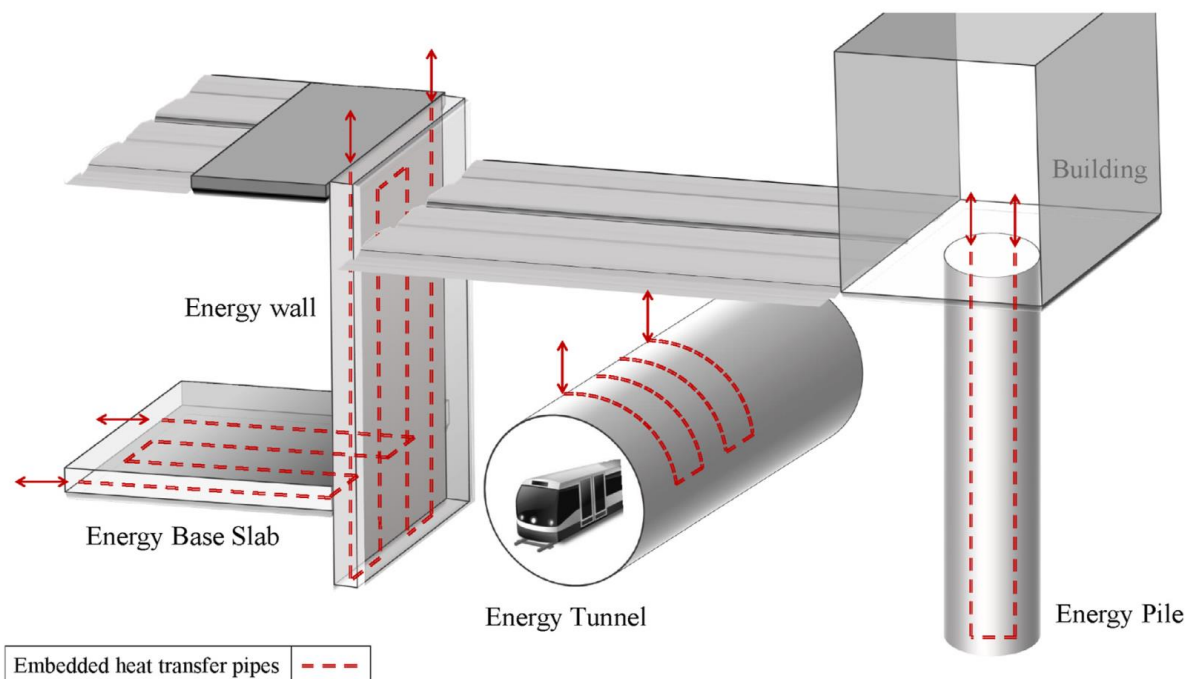


Fig. 8.1: Heat exchange pipes in different geostructures (Meibodi & Loveridge, 2022)

Fig. 8.2 illustrates different technical solutions to use geothermal energy in tunnels. Please note, that besides energy extraction also energy storage can be performed. Extraction and storage can be performed in a cyclic manner to use seasonal differences in air temperature and to extend the lifetime and efficiency of the heat exchange systems (e.g. preventing of cooling the rockmass). Fig. 8.3 illustrates the integration of geoenergy structures into district heating and cooling systems.

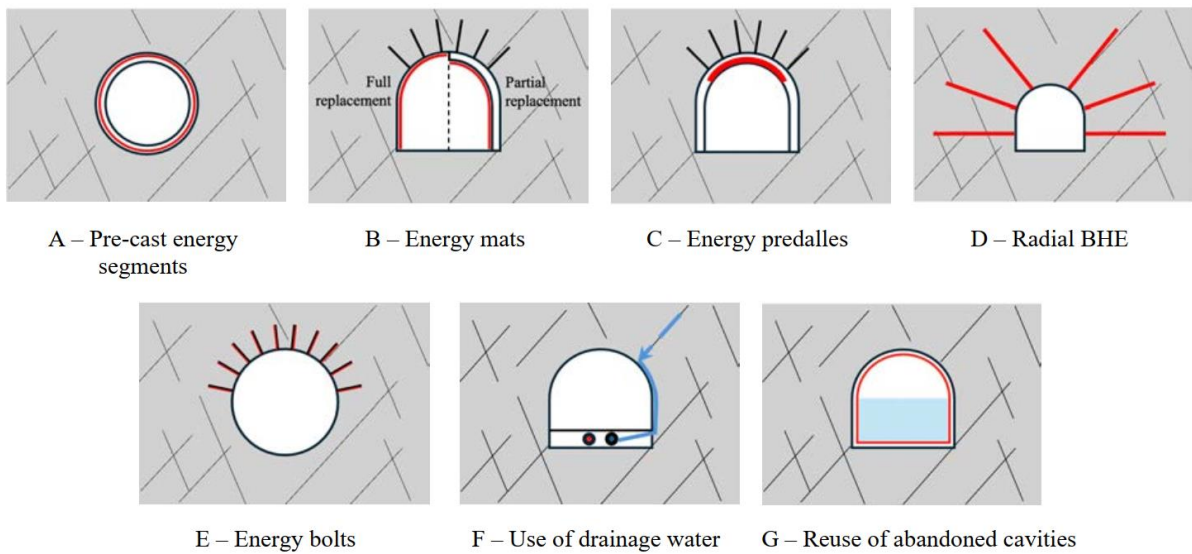


Fig. 8.2: Different technical solutions for heat exchange systems in tunnels (Barla & Insana, 2025)

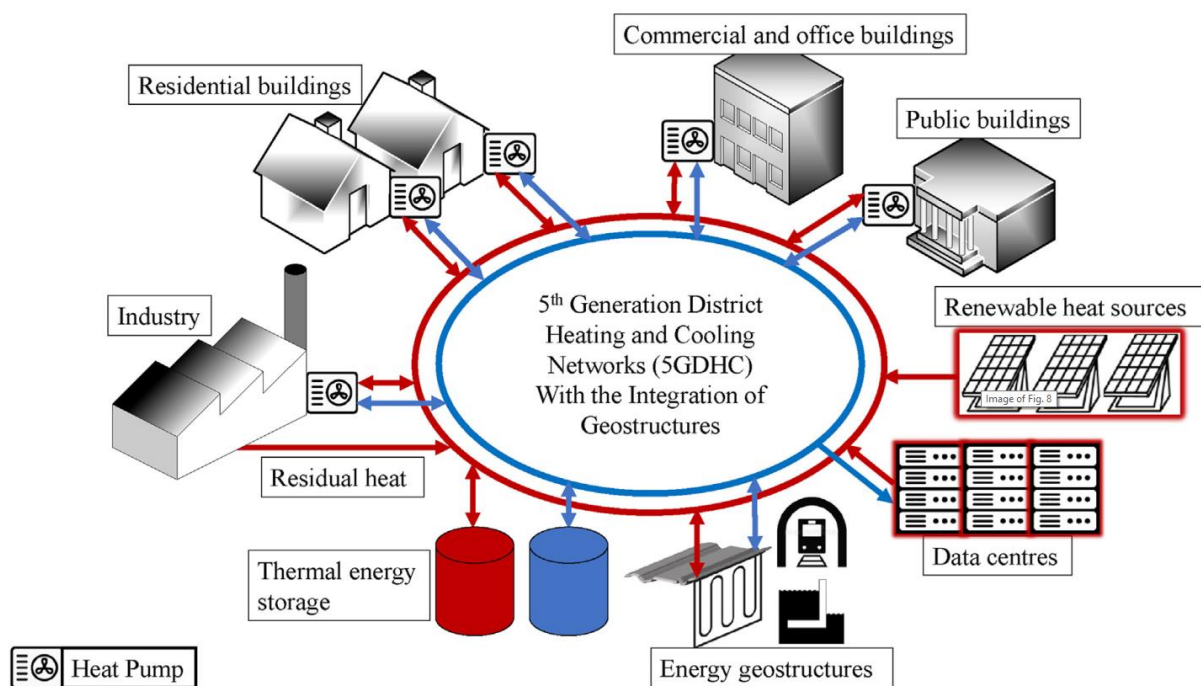


Fig. 8.3: Energy geostructures as part of heating and cooling networks (Meibodi & Loveridge, 2022)

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