Chapter 4
Applications of Geothermal Energy

Enhanced geothermal system Soultz-sous-Forets, Alsace, France

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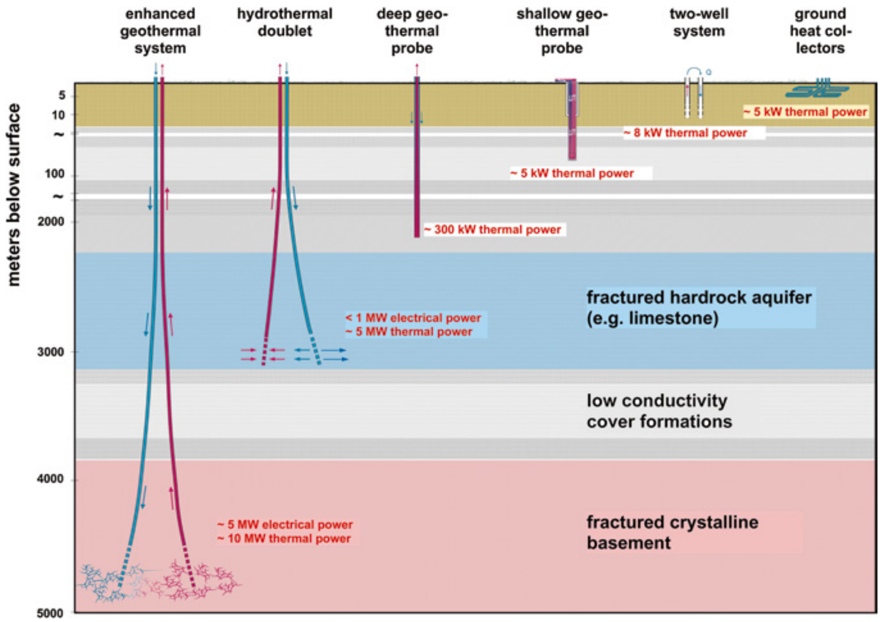


Fig. 4.1 Schematic illustration of different geothermal systems and their characteristic power output

The distinction between near surface and deep geothermal systems follows from the different depth levels of the geothermal reservoirs and different techniques of utilization (Fig. 4.1). Yet, the transition between the two worlds is smooth. Distinguishing the two main fields of geothermal energy utilization is useful, because their specific techniques for energy production require different geological and geophysical parameters for the description of the systems.

Deep geothermal systems exploit geothermal energy by means of deep boreholes. The mined thermal energy can be used directly and does not require further transformation.

Near surface geothermal systems, extract thermal energy from the uppermost layer of the earth crust. In most cases a depth of about 150 m is of interest. It may extend to a maximum of 400 m. Typical systems include: ground heat collectors, borehole heat exchangers, boreholes into groundwater, and geothermal energy piles. The exploitation is indirect and requires conversion with e.g. heat pumps. Direct use in the very low temperature range via heat pipes is under development. Railroad switch heaters and deicing of roads are typical potential applications.

With this definition of the boundary between shallow and deep systems, deep geothermal methods are employed at depth of 400 m and below. However, deep geothermal low-enthalpy systems in the proper and real sense are those at depth more than 1,000 m and above 60 °C. One needs to keep in mind, however, that in high-enthalpy fields high temperature fluids can be produced from boreholes in the range of hundreds of meters rather than thousands of meters as in the low-enthalpy deep geothermal fields.

4.1 Near Surface Geothermal Systems

Near surface geothermal techniques distinguish between open and closed systems with respect to the surrounding ground. The systems range from a few meters depth to some 10th of meters, rarely more than 150 m deep boreholes. Therefore, the temperature normally does not exceed about 25 °C.

Typical systems include: ground heat collectors, borehole heat exchangers, boreholes into the groundwater, and geothermal energy piles. At suitable temperatures, the utilization of waste water, mine water and tunnel waters also belong to near surface geothermal energy uses. In Switzerland, a number of road and rail tunnels produce warm water that is used for heating purposes. Examples include the Furka rail tunnel, the Gotthard road tunnel and the rail tunnel Ricken (Table 4.1). Utilization is made possible by means of heat pumps (www.geothermie.ch). A well-known geothermal system that uses waste water is the Olympic Village in Beijing, China. Waste water pumps heat and cool a total living space of 410,000 m^2.

Ground heat collectors consist of numerous horizontally installed plastic pipes of several hundred meters length at about 1–2 m depth (Fig. 4.2). The pipes must be mounted below the maximum penetration depth of winter frost. Also, the system needs to be above the level of solar regeneration in the summer. In the pipe system a circulating fluid (liquid) extracts heat from the ground. Strictly, ground heat collectors utilize not geothermal but rather solar radiation heat.

The most significant parameters controlling the thermal extraction output of such systems are the heat conductivity and heat capacity of the ground. The water and air content of the pore space and the ground temperature are important as well because of their effect on the key parameters heat conductivity and heat capacity. High porosity and void content of the ground typically reduce the heat conductivity.

If the groundwater table is low and the ground is in the vadose zone instead of the saturated zone, the voids are filled with air instead of water and the heat conductivity of the entire system is considerably lower (Sect. 1.4). Consequently, highly permeable sand and grit and water tables below 2 m below surface are problematic with respect to the efficiency of ground heat collectors.

The land required for ground heat collectors is large. The collector field cannot be overbuilt or covered because the system uses the solar heat input to the ground. If the groundwater table is temporarily low, irrigation of the ground heat collector

Table 4.1 Swiss tunnel water uses (Rybach et al. 2003)

Tunnel	Discharge (l/s)	Temperature (°C)	Thermal power (kW)
Gotthard	7,200	17	4,520
Furka	5,400	16	3,756
Grenchenberg	18,000	10	11,693
Rawyl	1,200	24	1,503

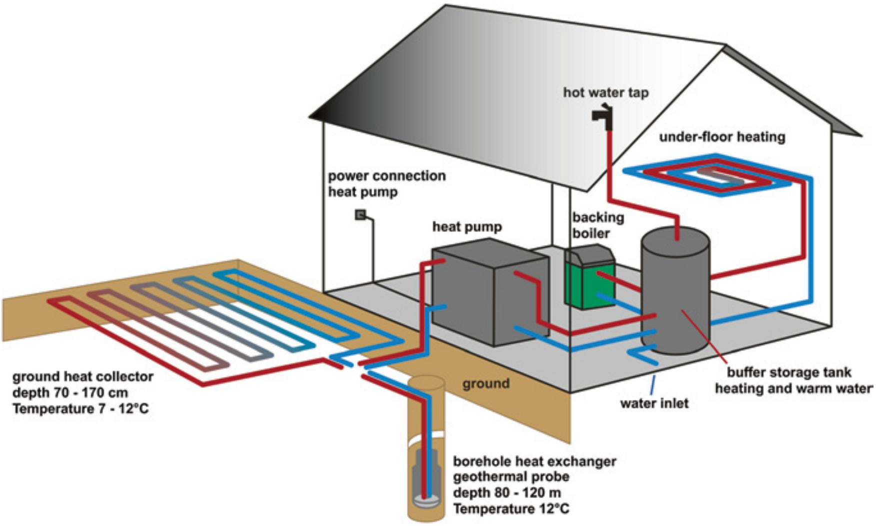


Fig. 4.2 Schematic illustration of ground heat collector and borehole heat exchanger for house heating

field may increase its efficiency. The systems require a considerable effort, which should not be undervalued, particularly if irrigation should be necessary.

Basis for planning for ground heat collectors are ground and soil maps and sections containing data on the structure of the near surface ground. These primary data are needed as input parameters for computer codes and techniques that model the heat conductivity structure of the ground as a function of soil compaction and water content (soil moisture). The computed models are essential for the final system design. Several computer models of variable complexity are presently available. However, no specific procedures for field tests have been developed so far. This is in marked contrast to thermal response tests for borehole heat exchangers. In addition, the computation tools cannot deal with heterogeneities of the ground. Furthermore, potential daily and annual variations of ground temperature and groundwater table are ignored in the system design. Nevertheless model computations are helpful and allow a generous dimensioning of the collector field and ensure that the spacing of the tubing is sufficiently wide, because of the potential for extensive icing of the ground.

Icing is an intrinsic system property of ground heat collectors; therefore, the systems cannot be operated with pure water. The system design must prevent massive freezing of the ground. The ground cools by operating the facility with the consequence of a retarded and shortened vegetation period. The biochemical activity of the soil biota including the production of humic and fulvic acids and other decomposition products of biomass may be altered. These chemical effects on the soil chemistry may trigger further chemical effects on the composition of seepage and groundwater.

A further reason why ground heat collectors cannot be run with pure water as a heat transport medium follows from its proximity to the surface. In wintertime, the system extracts heat from the ground at a low temperature level. Consequently, return temperatures commonly decrease to freezing conditions. Therefore, ground heat collectors need to be operated with special heat transfer liquids. For the approval and use of these liquids, detailed regulatory requirements must be obeyed, especially in groundwater protection fields.

Coiled tubes vertically installed in trenches and tube baskets are popular relatively recent new designs of ground heat collectors. Thermal power of the baskets ranges between 400 and 1,000 W depending on the size of the basket.

This technique of ground heat collectors is popular in e.g. Sweden and the USA where plots for family homes are typically larger than in e.g. densely populated central Europe and conform better to the area requirements for collector systems.

A further, relatively new type of near surface geothermal energy utilization uses building structures for heat exchange with the ground. Energy geostructures are elements of the foundation of a building in the ground that can be used for heating and cooling. Concrete is an ideal material for heat transfer because of its heat conductivity and heat storage capacity.

Foundation elements that function as geostructures are being equipped with plastic tubing for exchanging heat between the building and the ground for heating and cooling. The bundled tubing connects to one or several heat pumps. Proper hydraulic balancing increases the efficiency of the system. The foundation of the building serves as heat exchanger and geothermal system.

Energy piles or thermo-active piles are piles of reinforced concrete containing double or quadruple plastic U-tube heat exchanger or a network of polyethylene tubes. The tubes are completely embedded in concrete (Fig. 4.3). The heat transfer medium cycles between the pile and the heat pump in a closed loop. Depending on the energy demand of small or large industrial buildings, the installed thermal power of such systems ranges from 10 to 800 kW.

A very popular and widespread utilization of near surface geothermal energy is the use of borehole ground heat exchangers so called geothermal probes (Fig. 4.4). The heart of the system is a borehole of typically about 100 m depths. The deepest drill holes for geothermal probes reach 400 m. For many installations, more than one drill hole is used for energy exchange with the ground. In the borehole heat exchanger water or another heat transfer liquid such as water-anti freeze mixtures or also gases extract heat from the ground. The fluid circulates between a heat pump and the ground in a closed loop. The systems are technically mature and the installation is routine work for specialized commercial enterprises. Geothermal probes are also used for cooling in summer time. The geothermal borehole heat exchangers are particularly efficient in combination with solar-thermal installations. In Chap. 6, the combined systems will be presented in detail.

The geological structure and the ground properties are multifaceted and vary from place to place. The thermal properties of the ground differ from site to site accordingly. It is very important for the dimensioning of a geothermal installation to take the variability of the geological properties of the ground into account.

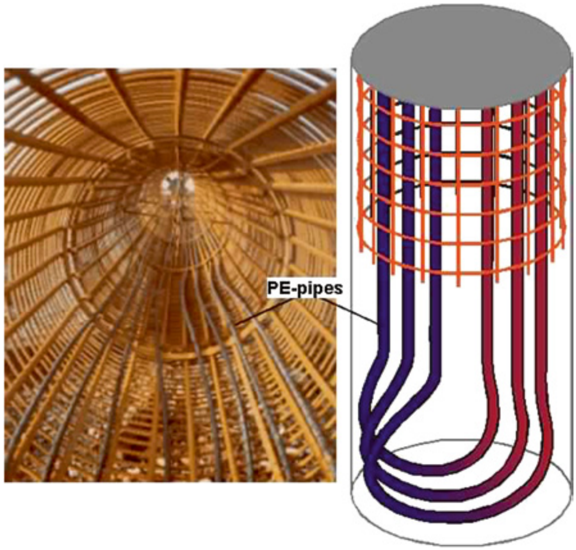


Fig. 4.3 Schematic illustration of an energy pile. In the indicated PE tubing a heat transfer liquid is cycled in a closed system

The thermal properties of some important types of rocks are compiled on Table 1.1. Highly permeable aquifers and aquifers with high groundwater flow velocities such as in karst areas are environmentally vulnerable. Drilling and casing of bores can be accompanied by mud losses, turbidity and chemical and microbial contamination and pollution of flowing groundwater. Drilling of a geothermal probe potentially intersects layers with different permeability, hydraulic situations and hydro-chemical properties. Tight annular void grouting and sealing of the annulus needs to conserve the layer separation. This is mandatory for any geothermal probe system. It is required by the matters of groundwater protection and it is essential for the efficiency and the economic lifetime of the installation.

Ideal sites are characterized by a uniform medium or low hydraulic conductivity. Areas with highly permeable karst aquifers or fractured hard rock aquifers are less favorable because of possible technical problems with drilling and casing. Drilling is often troubled by mud losses and can be associated with groundwater contamination. Moreover, it is often difficult to seal the annulus tight because of losses of cement slurry in the highly permeable voids. In such areas, higher costs must be expected for a professionally proper installed borehole heat exchanger. Occasionally the drilling is not successful and the wellbore must be abandoned and sealed.

In addition to the restricted potential of an area resulting from unfavorable geology, site-specific difficulties may trouble a geothermal energy project: Past losses, previous pollution, natural hazards, neighboring risks, adjacent bodies of water, protected areas, underground gas reservoirs, and others. Drilling into over- or under-pressured aquifers, or into layers of highly water-soluble minerals such as rock salt, gypsum or anhydrite may be potentially hazardous or cause technical drilling difficulties (Sect. 6.7).

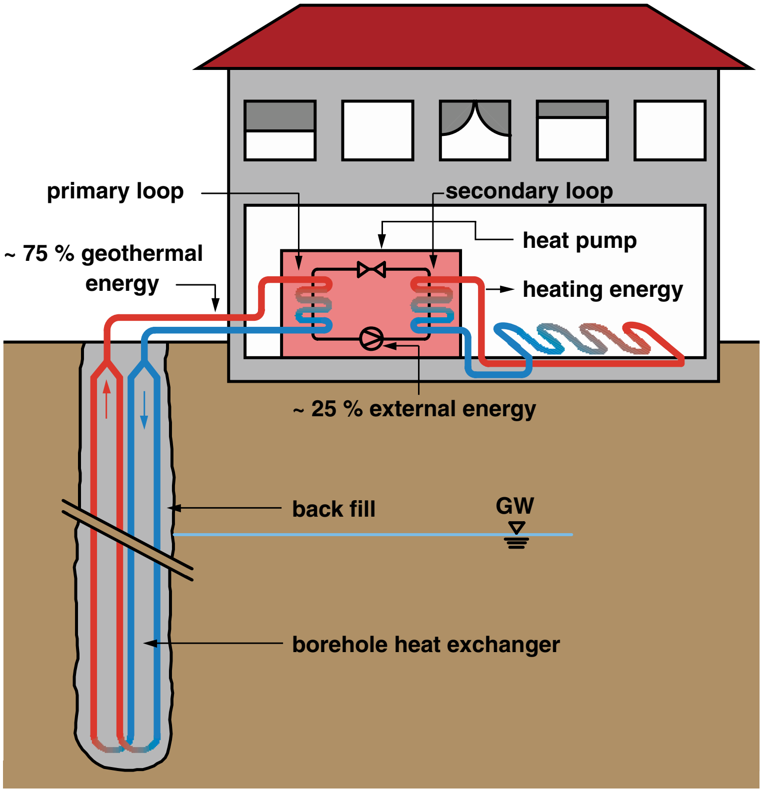


Fig. 4.4 General design of a borehole heat exchanger installation

Near surface geothermal energy can also be extracted directly from groundwater by means of an open two-well system. Heat is extracted from water of a production well and the cooled water re-injected and returned to the aquifer in a second well. It is important that the two wells do not influence each other thermally and hydraulically. The cool water must not be injected upstream from the production well. Furthermore, the chemical composition matters because many groundwaters have a disposition to precipitate scales. Detailed description of such systems is given in Chap. 7.

In order to utilize a near surface geothermal system for heating and heat production, the temperature of the circulated heat transfer fluid must be increased usually by making use of a heat pump. A heat pump is a device that transfers heat from a source at relatively low temperature to a heat sink at higher temperature using mechanical work. The mechanical work is provided by a pump driven typically with external electrical power. The device can be used for cooling (refrigerators and freezers are typical heat pump household devices) or heating (used in building space heating). Reversible cycle heat pumps are typically used for geothermal applications. The devices are equipped with a reversing valve so that the direction of heat flow may be reversed. The machines are evaporation–condensation systems and utilize the latent heat of condensation of a heat transfer fluid for space heating. The efficiency of a heat pump system using a specific heat source and operating at a particular temperature is characterized by the annual performance factor (APF). The ground source heat pump (GSHP) systems should operate at a minimum annual performance factor of four (Sect. 6.3). This means per unit of invested energy to drive the pump four units of energy should be extracted from the ground source. Investment costs, annual running costs, the primary energy requirement and the CO_2 emissions are the decisive criteria assessing the economical performance, the energy efficiency, and the environmental effects of ground source heat pump systems.

The legal and regulatory requirements for building and operating near surface geothermal systems vary from country to country (also between states and districts within countries). Normally they are based on groundwater and mining regulations. Typically, the authorities provide investors with guidelines and recommendations with detailed descriptions of all legal requirements for the building of the system of interest. Such guidelines also inform about existing restrictions for building a specific system. Potential restrictions include: groundwater protection areas, areas of unfavorable and difficult aquifer structure, drilling risks, and others. The guidelines may also assist developers and clients with recommendation procedures to follow in case of drilling into an artesian aquifer or under- or over-pressured confined aquifers, drilling into strata with gas over-pressure, drilling into large cavities or karst and into strata with soluble salts or with swelling minerals.

The utilization of geothermal energy for heating purposes requires significant initial investments. Prior to planning the system, potential and possible reductions of heating needs must be implemented. Highly recommended are thermal insulation measures, which directly reduce the need for heating. Included are masonry and façade insulation, thermally insulated high-quality windows and the like. Floor and wall heating systems significantly improve the economic viability of the heating system. Floor heating systems operating with supply temperatures of 35 °C or with concrete core temperatures of walls as low as 25 °C are far more economical than radiators running at 55 °C supplied by the heat pump. Economic and efficiency requirements also consider the hot water needs of a building (shower, washbasin, and the like). Expert advice and competent qualified planning of the total system assures an economic and environmentally friendly enduring operation.

4.2 Deep Geothermal Systems

Deep geothermal systems include hydro-geothermal low-enthalpy systems that use the heat stored in warm or hot water of deep aquifers (Fig. 4.5). The heat reservoir is exploited directly, generally employing a heat exchanger, occasionally also via a heat pump. The produced thermal water can be fed into the local and district heating grids or directly used in spas, heating of industrial complexes and heating of green houses. Conversion of the heat to electrical energy with supplementary technology such as Organic Rankine Cycle facilities or Kalina installations is possible above about 80 °C (Figs. 4.6a, b, c, and 4.7). However, economically feasible efficiency requires 120 °C or more.

Organic Rankine Cycle (ORC) plants work with an organic heat transfer fluid with a relatively low boiling temperature. The vapor phase of this fluid passes through a turbine thereby driving an electricity generator. Kalina installations use an ammonia–water mixture as a heat transfer fluid. The non-isothermal boiling of two-component fluid is a characteristic process of fluid mixtures (Kalina 1984; Ibrahim 1996).

The most popular kind-of-use of hydro-geothermal resources is the hydrothermal doublet (Chap. 8). The system is based on two wellbores drilled into a hot water aquifer, one of which is used as a production well where hot water is pumped from the aquifer to the surface, whereas the second well of the doublet is used for injecting the cooled water back into the subsurface reservoir. At the surface, the thermal energy of the hot water is transferred to a suitable fluid by means of a heat exchanger. The heat energy cannot be completely transferred and converted to electrical power. The hot water is typically cooled to about 55–80 °C only and, accordingly, much of the thermal energy remains in the thermal water. The residual heat has the potential to be utilized if appropriate customers and demand exist and the proper infrastructure can be installed. This also holds for enhanced geothermal systems (EGS) formerly known as hot-dry-rock (HDR) systems (Chap. 9). The economic success of a power plant depends much on selling the residual heat.

The cooled water with its residual heat is recycled to the aquifer from an injection well. The filter sections of the two wells of the doublet are at a exactly defined distance from each other (Fig. 4.5). Depending on the geological situation, injection may require a pump (Fig. 4.8). The need for recycling the produced hot water in a closed loop has several reasons. It is necessary to contribute to the recharge of the aquifer, because natural recharge of deep aquifers is a very slow process. Since a hydro-geothermal plant pumps large amounts of water it is simply necessary to make sure that the extracted water is replaced. Re-injection of cool water is also worthwhile for economical and practical reasons, because the waters contain typically high concentrations of dissolved solids and gases. For reasons of waste management, it is advantageous to dispose the waters in the original reservoir.

An example of a hydro-geothermal doublet is the plant of Riehen near Basel (Switzerland), which continuously supplies residential units in Switzerland and nearby Germany with thermal energy for heating (Fig. 4.8) since start-up in 1994. The two wells located at a distance of 1 km tap thermal water from the Muschelkalk aquifer at 1,547–1,247 m depth, respectively (Fig. 4.9).

Production and injection well of a hydro-geothermal doublet can be bored from one drilling site as inclined bores (Figs. 4.5, 4.10). This greatly reduces the area requirement of the surface installation of the plant. In the subsurface, bottom hole of the bores in the hot water reservoir are typically 1,000–2,000 m away from each other. The optimal distance of the wells must be determined pre-drilling

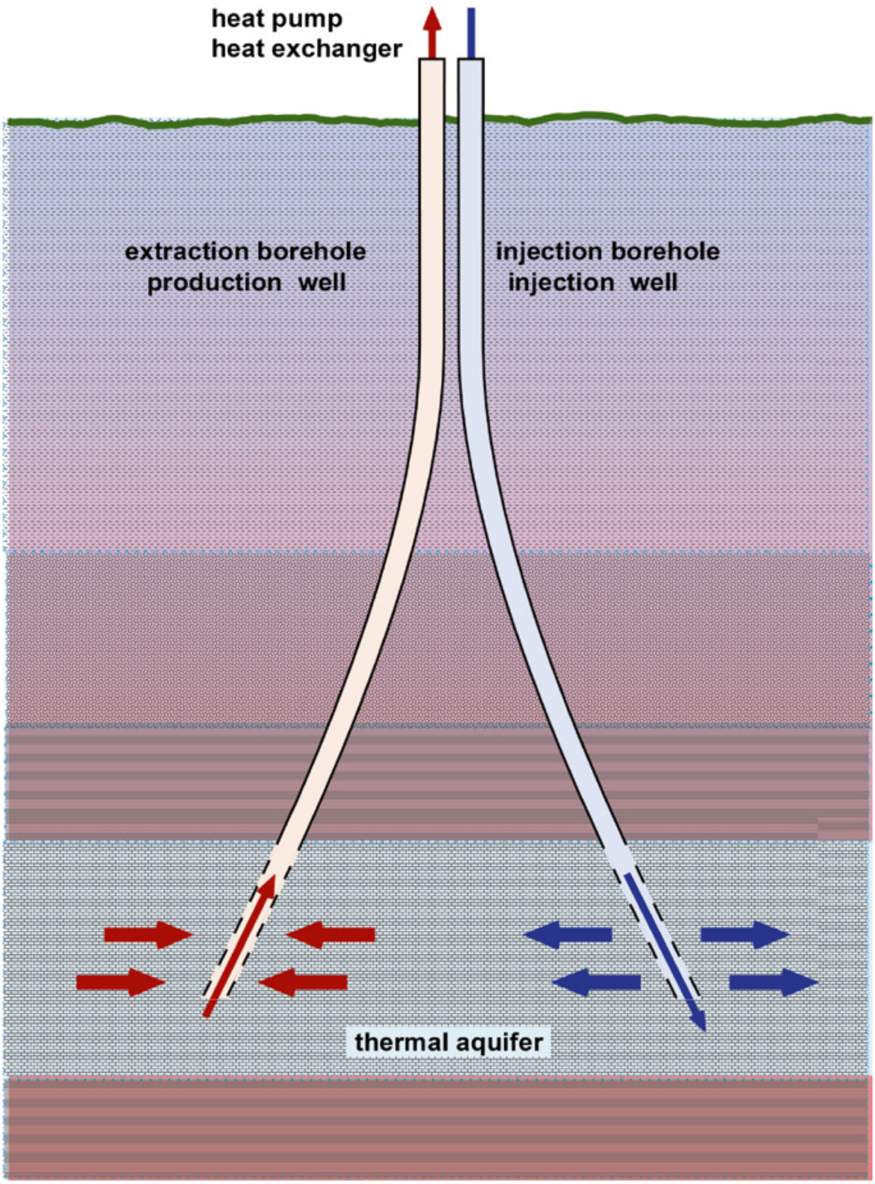


Fig. 4.5 Underground design of a deep geothermal open system installation (doublet, 1 producer, 1 injector)

by numerical modeling of the system. If the wells are too close to each other a thermal short-circuit is at stake. This means that the cooled re-injected water may reach the production well after a relatively short time of plant operation, cooling therefore the produced water. On the other hand, the wells should not be too far

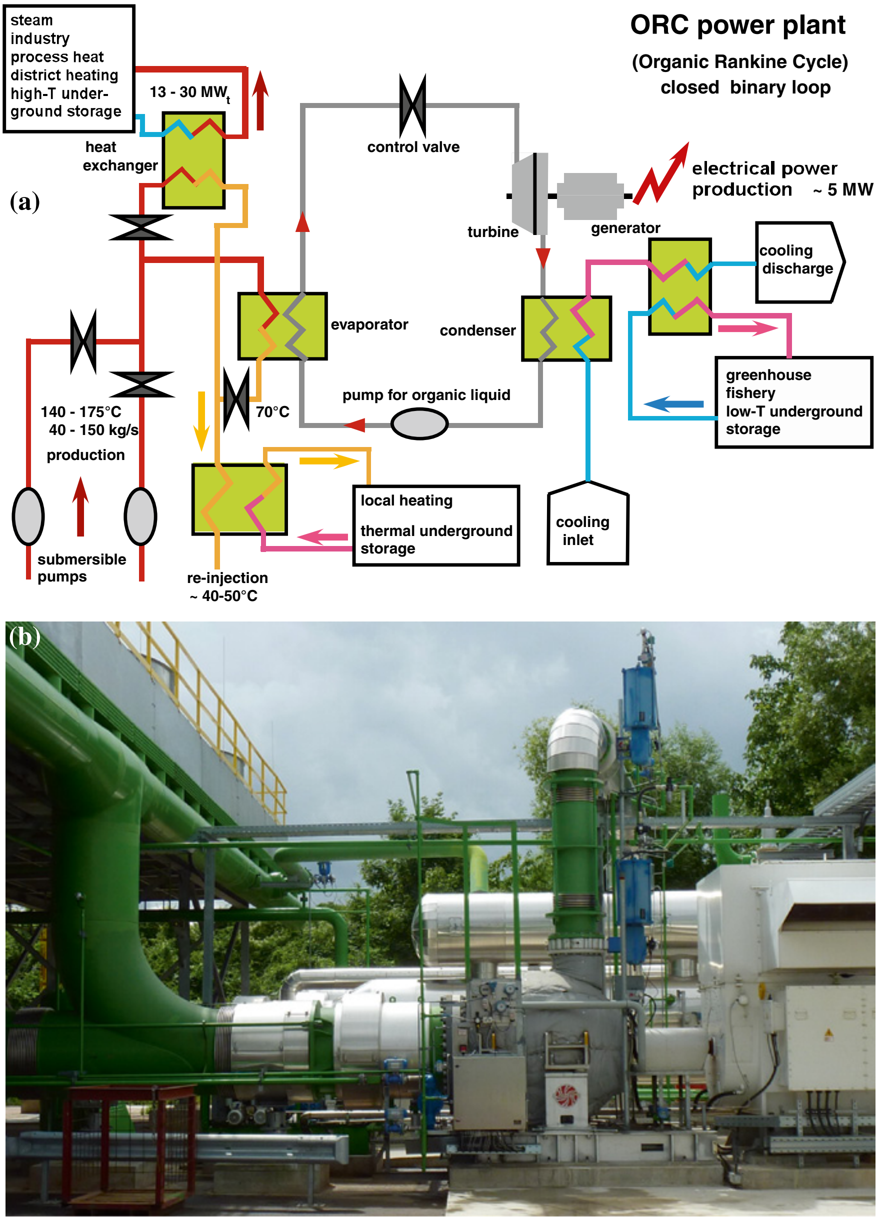


Fig. 4.6 Organic Rankine Cycle power plant: **a** concept and design (modified from Stadtwerke Bad Urach, Germany); **b** ORC cooling system; **c** ORC turbine (photographs **b** and **c** from Soultz-sous-Forets, France)

Fig. 4.6 continued

apart, because in this case the production well does not receive hydraulic support from the injection well. However, production depends on an intermediate time scale on the recharge of the aquifer by cooled water re-injection.

The pumped hot water and, after cooling, reinjected water circulate in a closed system that allows keeping the fluid under a defined pressure. This is necessary to prevent or minimize scales and mineral precipitations from highly mineralized and gas-rich fluids in the installations caused by pressure drop and gas loss. Ca-carbonates (calcite and aragonite) are among the most typical and widespread scales. Degassing of CO_2 from pumped hot water causes carbonates to precipitate in the pipe system even though the carbonates are more soluble in cold water, because CO_2-loss outweighs the temperature effect. In closed pipe systems, the pressure can be adjusted in such a way as to prevent degassing and scale formation. At some sites, small additions of a strong acid (e.g. hydrochloric acid) or other chemicals (organic inhibitors) may be needed to prevent scales (Sect. 14.3). The same applies to EGS systems. The cooled fluid can be recycled to the reservoir by free flow or by pumping depending on the hydraulic properties of the reservoir rocks. Typical reinjection pumps are multistage, single-entry centrifugal pumps in modular design with axial inlet and radial outlet.

Geothermal energy installations typically use two kinds of fluid production pumps: Line shaft pumps (LSP) operated at the surface and electric submersible pumps (ESP) (Fig. 4.8). The pumps for lifting hot fluids to the surface must resist high temperatures, high pressures and chemically aggressive and corrosive

Fig. 4.7 Wet cooling tower of the Kalina binary cycle power plant at Bruchsal in the upper Rhine river valley (Germany)

fluids thus belonging to the most stressed components of a geothermal power plant (Sect. 14.4). ESP lift the hot fluid with centrifugal force to the surface, where it is directed to a heat exchanger. The extracted thermal energy can then be converted to electrical power or directly fed into a district-heating grid. Combined heat and power improves energy efficiency and reduces emissions. These are particularly environmentally friendly and economical schemes.

Favorable fields for hydro-geothermal plants are above deep aquifers with high natural hydraulic conductivity and high temperatures. If the natural conductivity is too low for extracting hot water from the aquifer at the required rate the hydraulic structure of the aquifer needs to be improved by measures of artificial conductivity enhancement. Improvement measures include well shocking by sudden pumping, acidifying carbonate rocks, stimulation with high water pressures as well as combined stimulation and acidifying by pumping acid solutions with high pressure into the aquifer. Following the knowhow of the oil industry, improved extraction rates can be achieved by side tracking the well.

Utilization of thermal water by means of hydrothermal doublets for heating purposes is for the most part a mature technique. Hydrothermal installations that have been operating for dozens of years are currently in service worldwide.

Fig. 4.8 Fitting an electric submersible pump (*ESP*) into a production well of a hydrogeothermal doublet (2,500 m deep borehole Bruchsal, Upper Rhine River Valley)

Special cases of hydro-geothermal installations are balneological spas utilizing thermal deep waters. In addition to the use of hot water in the bathing pools, the pumped thermal water is also used for the heating of buildings in the local area. After use, the raw sewage is cleaned but not reinjected into the aquifer.

Hydro-geothermal systems include next to thermal aquifers also highly permeable fault and fracture zones in rock masses.

Besides the low-enthalpy hydro-geothermal systems, introduced above, high-enthalpy steam or two-phase systems are used for electrical power and thermal energy production (Sect. 4.4).

The future core systems of deep geothermal energy utilization are petrothermal systems that extract heat from hot rocks characterized by relatively low hydraulic conductivity. The systems are known under a variety of names reflecting the historical development of deep petrothermal techniques. The names include: Hot-Dry-Rock (HDR), Deep-Heat-Mining (DHM), Hot-Wet-Rock (HWR), Hot-Fractured-Rock (HFR) and Stimulated- or Enhanced-Geothermal-Systems (SGS, EGS). The original name HDR reflects the erroneous concept that basement rocks at

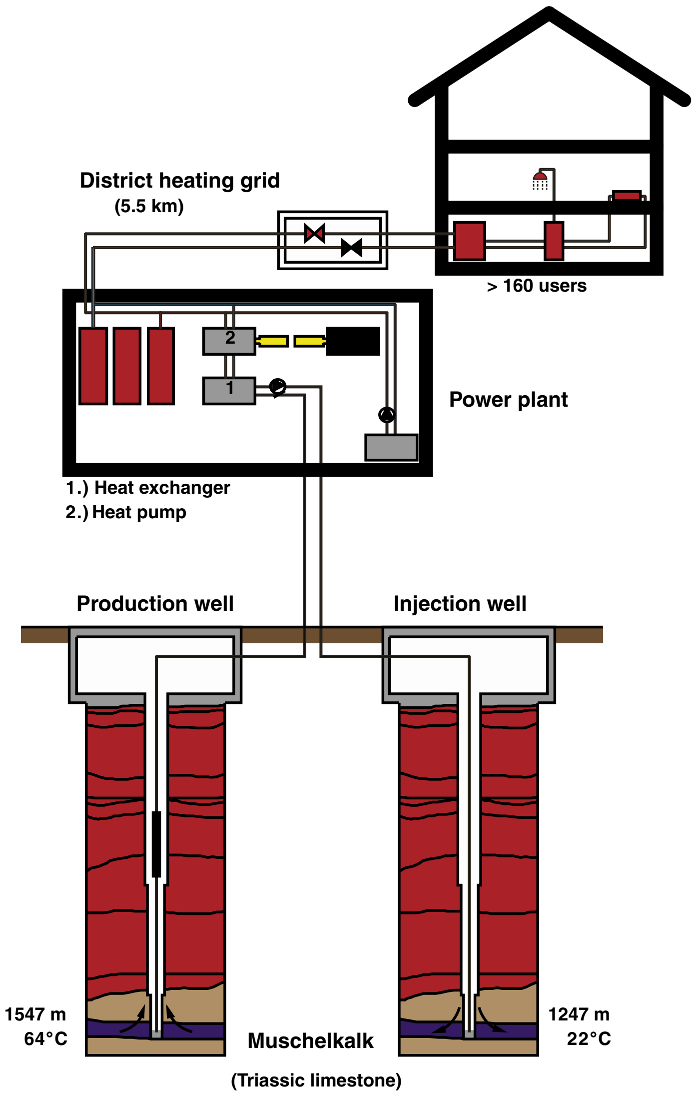


Fig. 4.9 The hydrogeothermal doublet system at Riehen (Basel, Switzerland), redrawn from documents of Gruneko Corp

great depth are dry and devoid of an appreciable permeability. After a large number of deep wells were drilled, it became evident that deep basement rocks (granites and gneisses) at several km depths are generally fractured and that the fracture porosity contains hot and usually salty water. The hydraulic conductivity of the hot rocks at depth is relatively large. In this book we will use the name Enhanced Geothermal Systems (EGS) for these techniques. EGS extract thermal energy stored in the rock mass, in contrast to hydro-geothermal systems that use the thermal energy from water stored in the pore space of rocks. Therefore EGS do not require a heat

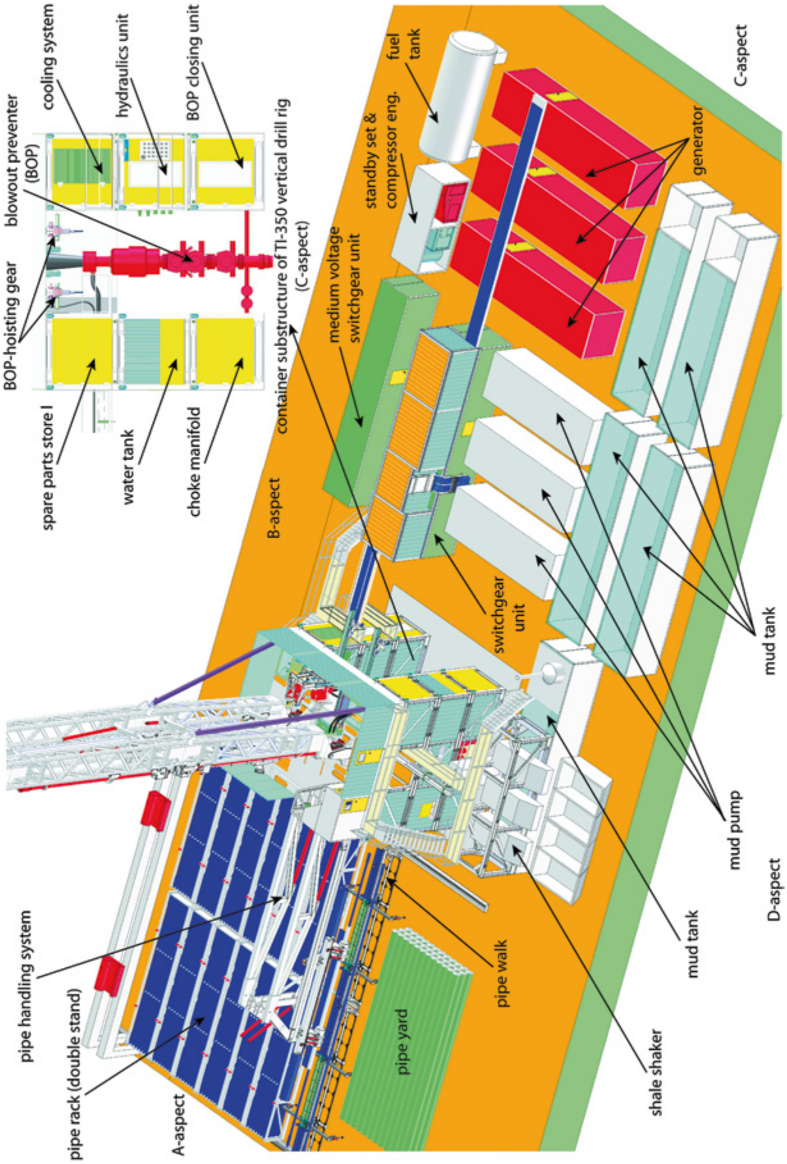


Fig. 4.10 Schematic illustration of a modern drilling site (the figure has been generously and kindly provided by Herrenknecht Vertical)

reservoir with aquifer properties in the hydrogeological sense. EGS primarily have electrical power production in mind. Consequently target temperature is 200 °C and beyond. The hot rocks, usually crystalline basement (granites and gneisses), function as a heat exchanger. Heat transfer to the surface is achieved by natural water present in the fracture pore space of the basement (Stober and Bucher 2007a, b; Bucher and Stober 2010). In crustal sections with average geothermal gradients, 5–7 km deep wellbores are necessary to reach the required rock temperatures (Chap. 9). Ongoing research explores the suitability of dense fractured sedimentary rocks for EGS applications. In the following, the basics of EGS are briefly outlined. A detailed treatment is given in Chap. 9.

The crystalline basement of the continental crust is generally fractured in its upper part. The fractures are the result of failure of stressed rocks in the brittle deformation regime in the uppermost about 12 km thick layer of the Earth. The fractures are flow paths for advective water transport. The hydraulic properties of the fractures depend on fracture aperture, surface roughness of fracture surfaces, connectivity and frequency of fractures and other parameters (Caine and Tomusiak 2003). The hydraulic behavior of the fractured basement corresponds to an infinite homogeneous low-conductivity aquifer (aquitard). High-pressure injection of water into the borehole increases the aperture of natural fractures and unlocks partly sealed fractures therefore improving the hydraulic conductivity.

Injected water passes the fractured rock heat exchanger at depth and scavenges heat from the rock mass. In addition, EGS use water as the heat transfer vehicle. Heat extraction at depth takes place in a nearly closed water cycle. The extracted thermal energy reaches the surface via a production well and can be converted to electrical power or (and) used directly for heating.

The EGS concept uses deep hot fractured rocks with relatively low permeability and does not depend on high-yield aquifers. In principle, an EGS project can be realized anywhere. However, reasonable projects aim for locations with raised geothermal gradients and a suitable tectonic setting. In 2011, only one single EGS plant is operational worldwide. It is located in Soultz-sous-Forêts (France) in the upper Rhine rift valley. The plant is in continuous operation since 2007. Although long-term experience does not exist, EGS will probably play an important role for the electrical power production in the years to come. Their fundamental advantage over other environmentally friendly energy systems is the supply of base load electric power.

Deep geothermal probes are, in principle, also a form of petrothermal systems. Here, thermal energy is extracted from any kind of rock or rock sequence using a closed loop of heat transfer fluid in a deep probe. Deep geothermal probes are used exclusively for heat supply. Because of the relatively low process temperature of the probes, electrical power cannot be generated with presently available technology.

The technology of deep geothermal probes is comparable to the ones of near surface probes. In a deep probe a heat transfer fluid is circulated in a single borehole to depths of up to 3,000 m (Fig. 4.11). The system does not require permeable rocks at depth and thus can be installed wherever. Particularly well suited

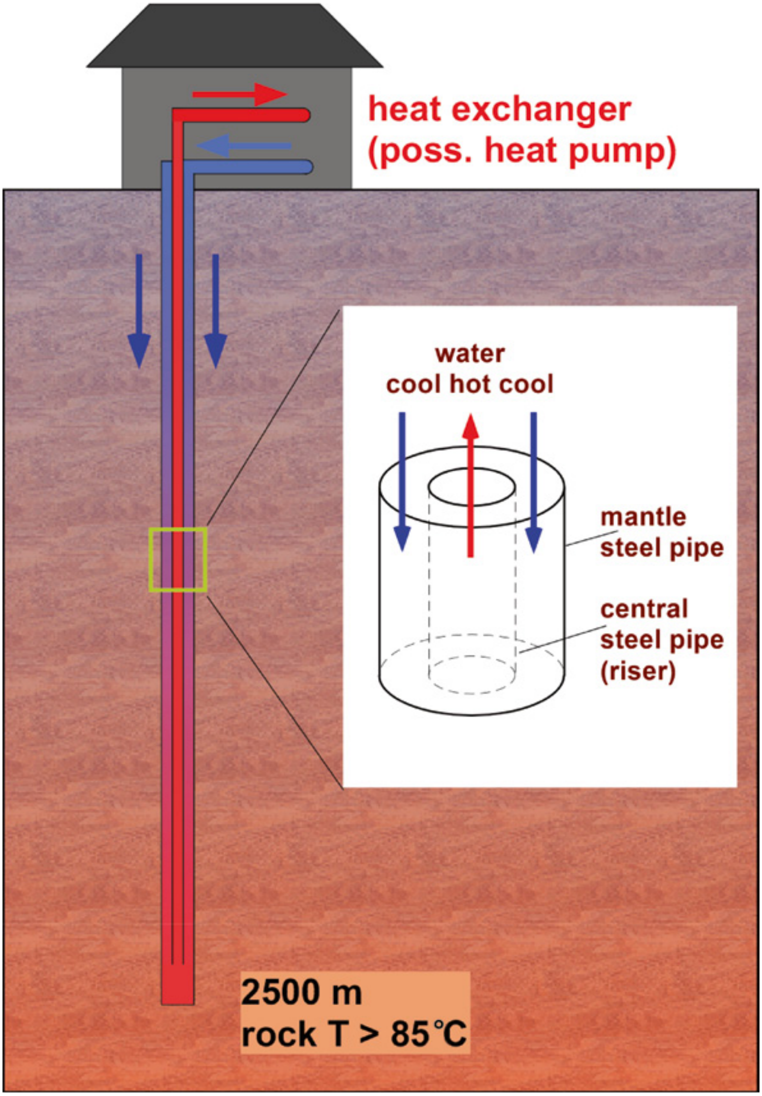


Fig. 4.11 Schematic drawing of a deep geothermal probe. It operates as a single borehole heat exchanger. The probe extracts heat at depth and transfers it to the surface heat exchanger (in combination with an optional heat pump) in a closed loop

for installation of deep geothermal probes are existing old abandoned deep wellbores (e.g. from the oil industry). Because of the closed loop, deep probes do not chemically interact with the deep heat reservoir. The utilization of the deep probes combines other heat producing facilities in an integrated heating central. The heat production of a deep geothermal probe can be in order of 500 kW depending on the local conditions. Examples of deep geothermal probes include the following locations: Prenzlau, Aachen, Arnsberg (Germany); Newcastle (UK).

Heat transfer from the hot rocks occurs by heat conduction through the grouting of the probe and the casing to the advecting fluid. Ammonia is a commonly used heat transfer fluid. The cool fluid slowly flows downward in the annulus of a double-containment pipe system and is gradually heated by the surroundings. The descend velocity is typically in order of 5–65 m/min. In a thermally insulated central pipe thermal energy is lifted to the surface by the heated fluid (Fig. 4.11). At the surface, heat is extracted from the hot fluid in a surface heat exchanger. The cooled fluid (15 °C) is pumped back to the annulus. The heat extraction process cools the underground in the vicinity of the probe.

The amount of effective heat produced by a deep probe depends primarily on the temperature of the ground. Thus areas with a positive thermal anomaly are economically particularly gainful. Further parameters controlling the productivity of a deep probe include the thermal properties of the ground, particularly the thermal conductivity, the total time of operation, the technical layout of the probe, and the thermal properties of the casing and screen materials used. Long and large-diameter probes have evidently a large heat exchange surface.

The structure of thick rock sequences is often characterized by properties that are transitional or mixed between hydro-geothermal and petrothermal systems.

Further fields of use of deep geothermal energy sources include: Heat from deep underground mines, rock caverns and storage of thermal energy in deep geological structures.

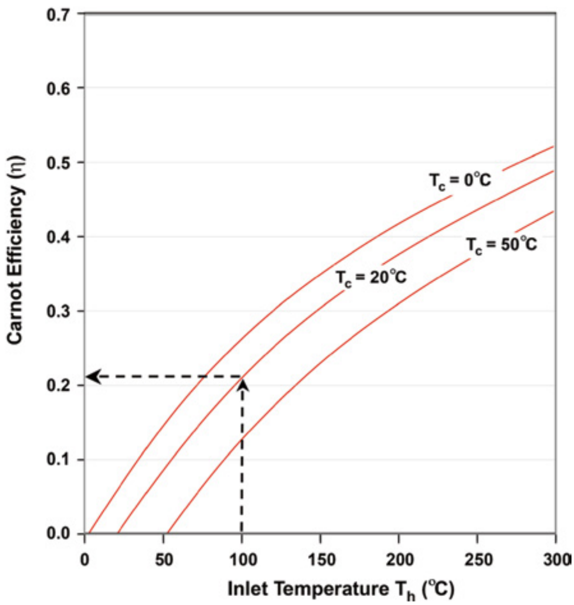
4.3 Efficiency of Geothermal Systems

Efficiency characterizes the degree of conversion of primary thermal energy to mechanical and finally electrical energy. Efficiency is the ratio of output to input, or benefit to effort. Because of the second law of thermodynamics, this ratio is always smaller than one. The Carnot efficiency η describes the maximum possible efficiency for any heat engine. It relates the maximum of work that can be produced by the system to the amount of heat put into the system. It is the theoretically possible maximum efficiency for an ideal heat engine. The efficiency of real systems is related to the Carnot efficiency η. The system design aims to reach efficiencies as close as possible to η. The Carnot efficiency η is defined by Eq. (4.1):

$$\text{The Carnot efficiency } \eta = 1 - \left(T_c/T_h\right) = W/Qth \tag{4.1}$$

where T_c corresponds to the temperature of the cold side, the outlet T of the fluid, and T_h the temperature of the hot side, the inflow T of the heat carrier fluid (both in Kelvin). This can also be expressed by the ratio of work done by the system (W) to the thermal energy added to the system (Qth). The Carnot efficiency η of a system with, for example, an inlet $T_h = 100$ °C (373 K) and $T_c = 20$ °C (293 K) has a theoretical maximum of 0.21 (21 %) (Fig. 4.12).

Fig. 4.12 Diagram showing the Carnot efficiency (Eq. 4.1) as a function of the inlet temperature *Ti* (here in ˚C) for three different outlet temperatures *Tc* (also in ˚C)



The physical upper limit of thermal efficiency for power stations driven by thermal water (hydro-geothermal or EGS plants) of 100–200 °C is about 12–22 %. In this temperature range, electricity production is feasible only with binary loop plants. In 2013, two different systems are available on the market, systems based on the Organic Rankine Cycle (ORC) and systems based on the Kalina Process. ORC systems use organic fluids, typically isobutane, as heat transfer fluid. Kalina systems work with an azeotropic mixture of ammonia and water. Azeotropic mixtures boil over a certain temperature interval called temperature glide. The power output to the grid of air-cooled Kalina systems tends to be higher than that of ORC systems at low input temperatures, whereas ORC plants tend to be better performers at higher input temperatures. Kalina systems withdraw less thermal energy from the thermal water than ORC systems but convert it to electrical power with higher efficiency. In the low temperature range ORC systems suffer from low thermal efficiency that follows from a high auxiliary power requirement of the cooling system, especially when air cooled (Park and Sonntag 1990).

All geothermal power plants produce heat in addition to electrical power (Fig. 4.13). This heat needs to be used in combined heat and power systems. The maximum use of the side product heat determines the economic success of a geothermal power plant. Moreover, production of electrical power only and pointlessly wasting the co-produced heat would be ecologically insensitive and ignorant.

The efficiency of electrical power production is relatively low. Taking the auxiliary power requirement of the production pump and the cooling loop into consideration also, the typical efficiency of the total system is about 5–7 %. Clearly there is room for improvements. However, if the residual heat of the thermal water after

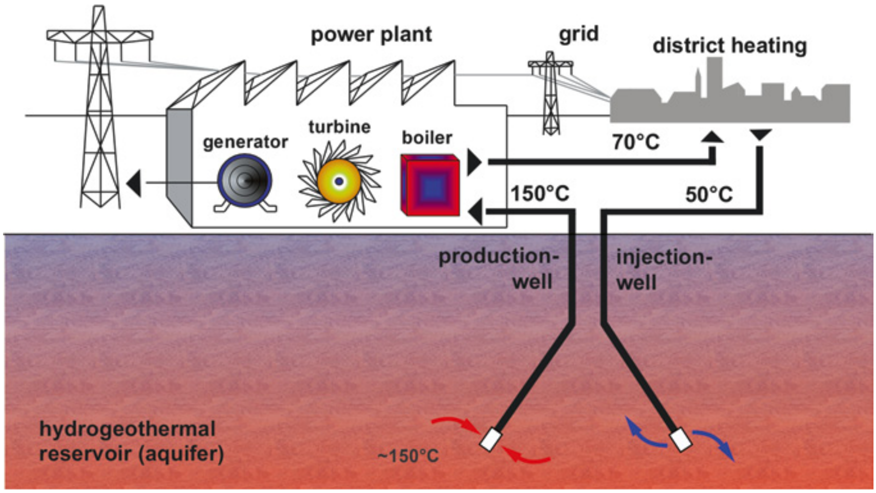


Fig. 4.13 Schematic diagram of a hydrogeothermal system with a binary system power plant converting a part of the produced thermal energy to electricity and utilizing an other part for district heating

electrical power production is used for district heating (Fig. 4.13) and other purposes, the environmental balance of the total system is determined by the quantity of supplied heat. Geothermal energy systems can also be combined with other heat sources including biogas plants and hybrid plants thus improving the environmental balance.

The conversion of thermal energy to mechanical or electrical energy in thermal plants inherently produces waste or process heat that needs to be discarded. If the process heat can be transferred to lake or river water a very low temperature T_c (Eq. 4.1) and a corresponding high efficiency can be attained. However, at many sites potential environmental degradation or lack of cooling water in sufficient quantities requires cooling by means of cooling towers. Wet cooling towers (Fig. 4.7) and dry cooling towers (Fig. 4.6b) transfer process heat to the atmosphere.

4.4 Major Geothermal Fields, High Enthalpy Fields

The annual global production of electrical power from geothermal sources is about 11 GW_{el} (2010), thereof 1.4 GW_{el} in Europe (Bertani 2010; IEA-GIA 2012). Most of the geothermal electricity is produced in high-enthalpy fields that reach high temperatures at shallow depths. The electricity is generated in dry-steam and flash-steam power plants. Examples are the Coso geothermal field at the western edge of the Basin and Range geologic province in eastern California (USA), the Wairakei geothermal field in the Taupo Volcanic district in New Zealand, the Mori geothermal field in Hokaido (Japan), the Hatchobaru geothermal field in central Kyushu (Japan) and many other similar systems worldwide.

These power plants of high-enthalpy fields function as open system geothermal installations. The systems use steam produced by decompressing the thermal heat transfer fluid to drive turbines for electrical power production (Fig. 4.14a–c). The minimum operation temperature in flash-steam plants is 175 °C. The turbine converts geothermal energy into mechanical energy that is converted to electrical energy by a generator. A part of this electrical energy is consumed by pumps and other machinery of the power plant; the net power is fed into the grid.

Electrical energy production from geothermal sources in closed binary-loop low-enthalpy systems such as ORC and Kalina plants (Fig. 4.14c) is a relatively new technology that has been installed at relatively few locations worldwide although suitable locations are far more frequent. There is an enormous potential for future development and expansion of deep low-enthalpy systems. Many projects are in the planning stage (2013). A major disadvantage of high-enthalpy fields is their limited occurrence in volcanic and tectonically active areas along plate boundaries or extensional basins. A major breakthrough for increased geothermal energy utilization must come from petrothermal EGS systems in addition to further development of hydro-geothermal systems.

In Europe, Italy has the highest installed power of about 800 MW_{el} and is well ahead of Iceland with 202 MW_{el} (2005). In Tuscany (Italy) favorable geological settings, very early development and the resulting experience led to a steady growth of the geothermal energy industry. However, the big four in the world are (installed capacity 2005, Bertani 2007): USA 2,564 MW_{el}, Philippines 1,930 MW_{el}, Mexico 953 MW_{el} and Indonesia 797 MW_{el}. Other major producers of electrical power from geothermal resources include (in MW_{el}) Japan (535) and New Zealand (435). Much of the power of the high-enthalpy fields in these countries is produced by dry-steam plants.

Iceland uses mostly geothermal resources from high-enthalpy fields related to the volcanic mid-ocean ridge and the Iceland mantle plume. However, the country also installed some binary loop plants in low-enthalpy fields in recent years. The important Russian high-enthalpy fields and the associated geothermal plants are all situated in Kamchatka and on the Kuril islands. The total installed capacity is 80 MW_{el}. Turkey has a promising geothermal energy potential also, although the installed power is only 20 MW_{el} today (2005). 10 high-enthalpy fields are on the list of identified 170 geothermal heat reservoirs. Some of the boreholes reach 200 °C already at 800 m depth.

The most important and largest high-enthalpy geothermal field in the world is "The Geysers" in California (USA). The field has 888 MW_{el} installed capacity and uses a 300 °C dry steam reservoir at 600–3,000 m depth (deepest well: 3,900 m). The power is produced from 100 km^2 drilled area, 424 production and 43 reinjection wells. Average steam temperature is 235 °C (at 12.4 bar) and the average flowrate per well 5 kg/s. The steam is produced from a sandstone and graywacke reservoir that is heated by a magma chamber at greater depths.

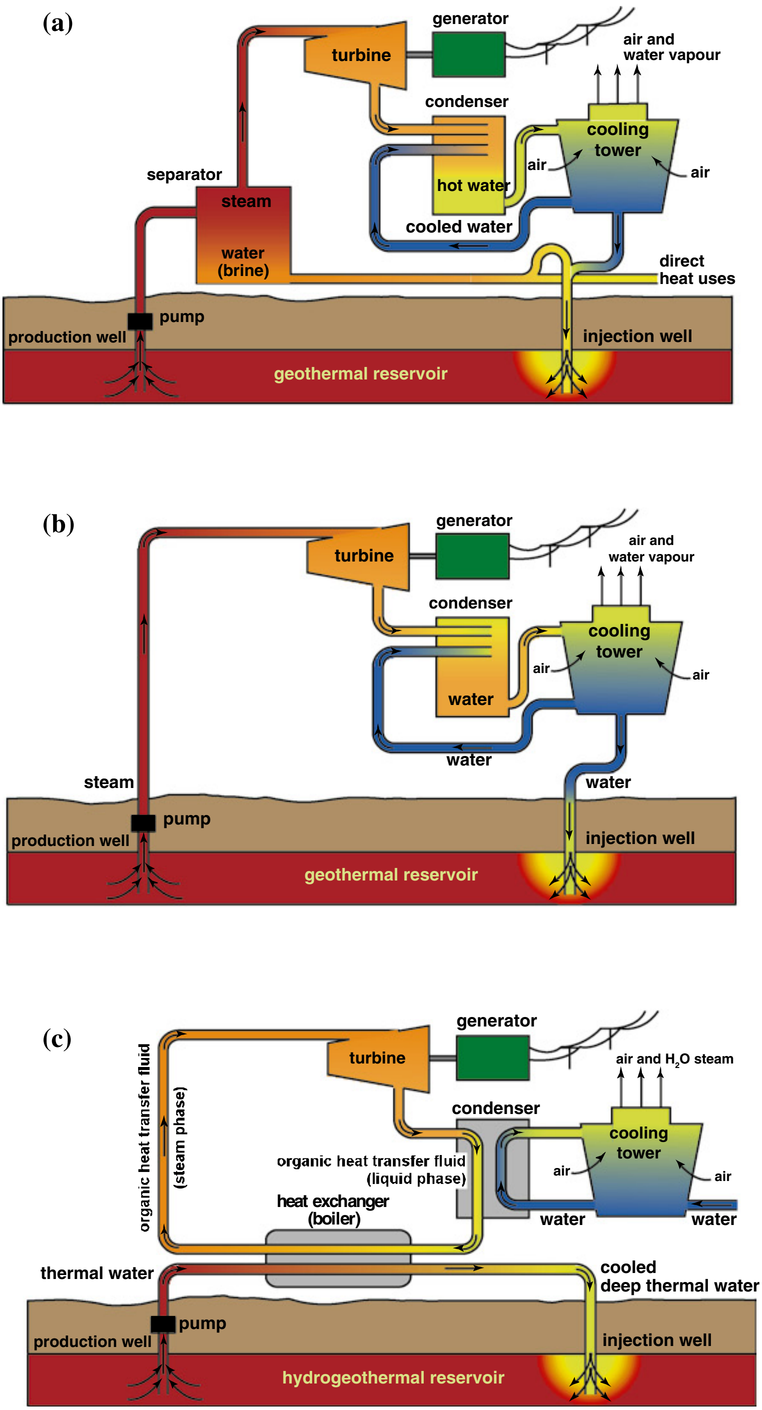


Fig. 4.14 Process diagrams for three common types of geothermal power plants: **a** Flash steam plant. **b** Dry steam plant. **c** Binary cycle power plant

As a result of the power production and the associated reduction of steam pressure the ground became seismically active after about 1975. Seismic events reached magnitude $M_L = 4$ (Sect. 10.1). Seismic tremors correlate with the power production and the related rate of steam extraction from the reservoir even though a part of the condensed and cooled steam is reinjected to the reservoir. The steam pressure in the reservoir is decreasing by about one bar annually since 1966. The increased seismicity relates to reservoir compaction because of reduced pore pressure due to withdrawal of fluid and thermal contraction resulting from cooling (Nicholson and Wesson 1990).

"The Geysers" reached peak production of 1,900 MW in the year 1989. After that, maximum continued steam withdrawal resulted in aging of the reservoir and a decrease of steam pressure. In the last decade additional water injections partly compensate the withdrawals. At present (2011), about 800 kg/s cleaned municipal wastewater from Clear Lake and Santa Rose props up the reservoir. The measures slowed down reservoir degradation and total power output resumed.

The second largest geothermal field is Cerro Prieto, Mexico 720 MW_{el} with 149 production and 9 reinjection wells. The liquid fluid reservoir at 2,800 m depth is in the temperature range of 300–340 °C. The Cerro Prieto Geothermal Power Station is the largest geothermal power station in the world with plans for expansion up to 820 MW_{el} by 2012. The facility is located in south Mexicali, Baja California, in Mexico, and is built in five individual units.

The Malitbog Geothermal Power Station on the Philippines is the largest single geothermal power plant with a capacity 233 MW_{el}.

The history and development of the high-enthalpy field Larderello in Tuscany (Italy) is separately described in Sect. 2.2. Today (2011), the total installed capacity of the Larderello geothermal plants is 545 MW_{el} equivalent to the power of a modern coal-fired power plant. Like with all other plants in high-enthalpy fields, the production costs for the unit of electrical power output is low because there are no fuel costs (coal, oil, fuel rods). Some of the production wells produce up to 350 t/h (100 kg/s) steam at a temperature of 220 °C. The installations at Larderello inject all water not used in the cooling loop back into the reservoir. However, the losses or unbalanced difference between extraction and reinjection caused deterioration of the steam pressure and, as a result, a decline in power production. In the reservoir, the thermal energy is still there but the heat transfer fluid, here steam, is lacking or no longer present in sufficient amounts.

The plant operator ENEL (Ente Nazionale per l'Energia eLettrica) designed a program to revitalizing the high-enthalpy field. The exploited steam reservoirs are replenished with water from neighboring fields. New deep wells replace older shallow wells. This new technique permits to increase the working pressure from presently 4.5 to 5.0 bar to 12 bar. New 60 MW power blocks replace the array of old 20 MW turbines.

Because of the geologic position of Iceland on the Mid-Atlantic Ridge and above the Iceland mantle plume, a multitude of volcanoes is presently active on the island. The geothermal fields associated with the volcanoes are extensively utilized and Iceland is the leading geothermal country (Sect. 2.2). 53 % of the used primary energy is geothermal energy. Five larger geothermal power plants produce 25 % of the island's consumption of electricity and 90 % of the households are supplied with heat. The installed geothermal capacity of the plants on Iceland is about 625 MW_{el}.

The hot water for the capital city of Reykjavik with its 120,000 inhabitants, including the hot water for deicing installations for sidewalks and roads, is supplied by a warm water reservoir, the so-called Perlan at an elevated height above the city making pumps unnecessary. The reservoir consists of five single tanks with 4,000 m^3 capacity of 85 °C hot water each. The hot water is produced from 70 drilled wells in the city.

The hot waters produced from high-enthalpy fields in Iceland, like in any other area, typically contain a large amount of dissolved solids. The hot waters are normally not in chemical equilibrium with the minerals of the reservoir rocks. Therefore, the waters react with the rock matrix in complex hydrothermal reactions. The total mineralization increases with temperature because for many substances and minerals the solubility increases with temperature and since the kinetics of mineral dissolution reactions increases with temperature (Chap. 14). Because of the water–rock interaction, the waters regularly contain high concentrations of dissolved silica. At low temperature, only small amounts of silica can stay in water under equilibrium conditions. Thus, precipitation of silica sinter and silica scale is a common occurrence and problem in high-enthalpy fields. The rate of silica precipitation depends on the temperature and the composition (salinity) of the water, which allows to partly controlling the site of precipitation in the system to some degree. The efficient pressure-controlled separation of steam and liquid (Fig. 4.14a–c) is crucial to avoiding silica scales in surface installations, such as turbines or heat exchangers (Sect. 14.3). The expanded steam from high-enthalpy reservoirs on Iceland contains 5 mg/kg dissolved solids only in contrast to the separated liquid phase that contains 45,000 mg/kg total dissolved solids (Giroud 2008). The major components in most thermal fluids are sodium, potassium and calcium and the associated anion is normally chloride. Dissolved silica is typically in the range of 600–700 mg/kg SiO_2 (this compares to the equilibrium concentration of 6 mg/kg at 25 °C). Boron, fluoride, barium, mercury and other trace elements can be significantly enriched. The high TDS of the produced fluid and solutes that are partly difficult to cope with are a serious challenge to the high-enthalpy geothermal plants. Some of the reservoir fluids also contain high concentrations of dissolved gasses, which are not condensable like CO_2 and H_2S. Degassing of high CO_2 concentrations promote calcite scale formation and CO_2 is corrosive. High H_2S concentrations may cause metallurgical problems, react with metal surfaces, cause corrosion, fatigue and cracking (Sect. 14.3).

The Iceland Deep Drilling Project (IDDP) with several international partners drilled a wellbore into a hot-fluid reservoir containing H_2O in its supercritical state. Reservoir conditions are $T > 375$ °C at $P \sim 225$ bar. The critical point of H_2O (CP) is at the coordinates $T = 374$ °C and $P = 221$ bar. It is planned to utilize the supercritical fluid for power production. The development and utilization of supercritical fluid reservoirs appears attractive because the system efficiency may be improved by a factor between 5 and 10 in relation to the produced fluid volume.

Wells on Iceland may reach 360 °C at a depth of only 2,200 m in some places, meaning that P–T conditions are close to the critical point of H_2O. The fluids are often toxic and very corrosive. Further challenges are scales that are difficult to control and problematic to remove and dispose without harm to the environment.

The development of very deep high-enthalpy reservoirs for industrial use is presently not workable due to technical reasons. At temperatures of 400 °C and more, the temperature resistance of materials, of drilling mud and geophysical instruments, the materials strength and limited hook load (<500 t) of drilling rigs pose serious hindrances.

Projections predict a total installed world capacity of geothermal electricity production of 140 GW_{el} for the year 2050 (Friedleifsson et al. 2008). This ambitious goal can only be reached if the EGS systems, which are relatively independent on location in contrast to high-enthalpy plants, are being further industrially developed. Additionally, existing geothermal fields must be further developed with increasing numbers of production and reinjection wells. Systems with production wells only are not environment friendly and economically not profitable. Geothermal reservoirs must be backed, that is to say they must be replenished and renewed. Reinjection recycles the high-TDS fluids to the original reservoir, which also helps to prevent disagreeable subsidence formation, reduction of permeability and decrease of production rate. The development of a geothermal field must be inclusive and integrate all potential users from the beginning of the planning stage: In addition to the electricity production side, this includes the utilization of the produced heat in industry, district heating, sports facilities, green houses and other secondary heat users.