8.3 Types of geothermal energy use

Geothermal energy can be used directly, i.e. without any further conversion, as heat. The direct application of geothermal heat is referred to as *direct use*. Alternatively, geothermal heat can be converted into other types of energy at the expense of some energy for the conversion. *Electric power generation* requires conversion into electricity. Direct use exploits the resource more efficiently than power generation as no energy is lost during conversion of heat into electricity. However, heat cannot be transmitted over distances of more than some kilometers at most without a notable reduction of efficiency due to inevitable heat losses. There has been a long tradition of direct use of geothermal heat in various human cultures over several millennia, mostly associated with (but not restricted to) hot springs. Although there is no exact starting date for the direct use of geothermal heat, it is well known when geothermal heat was supplied to a large-scale municipal district heating system for the first time: in Iceland in the year 1930 [01Fri]. Since then, Iceland has become independent of fossil fuels for heating, eliminating the serious prior pollution problems related to the burning of black coal in winter. In contrast to direct use, it is exactly known where and when geothermal heat was first converted into electric power: in Lardarello, Italy, in the year 1904, a century ago when the engineer Count Piero Ginori Conti succeeded in producing sufficient electricity from geothermal steam to power five electric light bulbs.

Different technologies are used to produce geothermal heat. They are based on either heat conduction or advection:

1) In conductive heat production, heat diffuses into an isolated underground heat exchange system without any exchange of substance (see Sect. 8.3.1.1.1 and Sect. 8.4.1.1). This technique is employed in direct use, predominantly for shallow heat production systems.
2) Advective heat production is based on the production of hot fluids, mostly brines, from underground reservoirs at appropriate depths (see Sect. 8.3.1.1.2 and Sect. 8.3.2). This technique is used both for direct use (see Sect. 8.4.1.2) and power generation in low enthalpy[1] and medium or high enthalpy fields (see Sect. 8.4.2.1), respectively, depending on the temperature of the produced fluids (Table 8.19).

Of approximately 100 hydrothermal systems studied worldwide, less than 10% are vapor dominated dry steam fields, 60% are water dominated wet steam fields, and 30% produce hot water [02Bar].

Table 8.19. Classification of geothermal reservoirs [02Bar].

Type	Resource	Temperature range [°C]	Energy content
Water dominated	Warm water	< 100	Low enthalpy
	Wet steam	100 - 150	Medium enthalpy
Vapor dominated	Dry steam	> 150	High enthalpy

8.3.1 Direct use

In direct use geothermal energy is employed directly as heat without further conversion in other types of energy. By the year 2005, the global annual production of direct use geothermal energy amounted to 72622 GW h or 261 PJ [05Lun]. Large as this figure may appear, it amounts to just about one per cent of the primary energy consumption of 14319 PJ in a medium sized, developed industrial country like Germany in the year 2004 [04BMW]. Figure 8.26 shows, on a logarithmic scale, the contribution of the top

[1]) Enthalpy $H = E + P \cdot V$, where E is internal energy, P pressure and V volume, see Sect. 8.1.4.

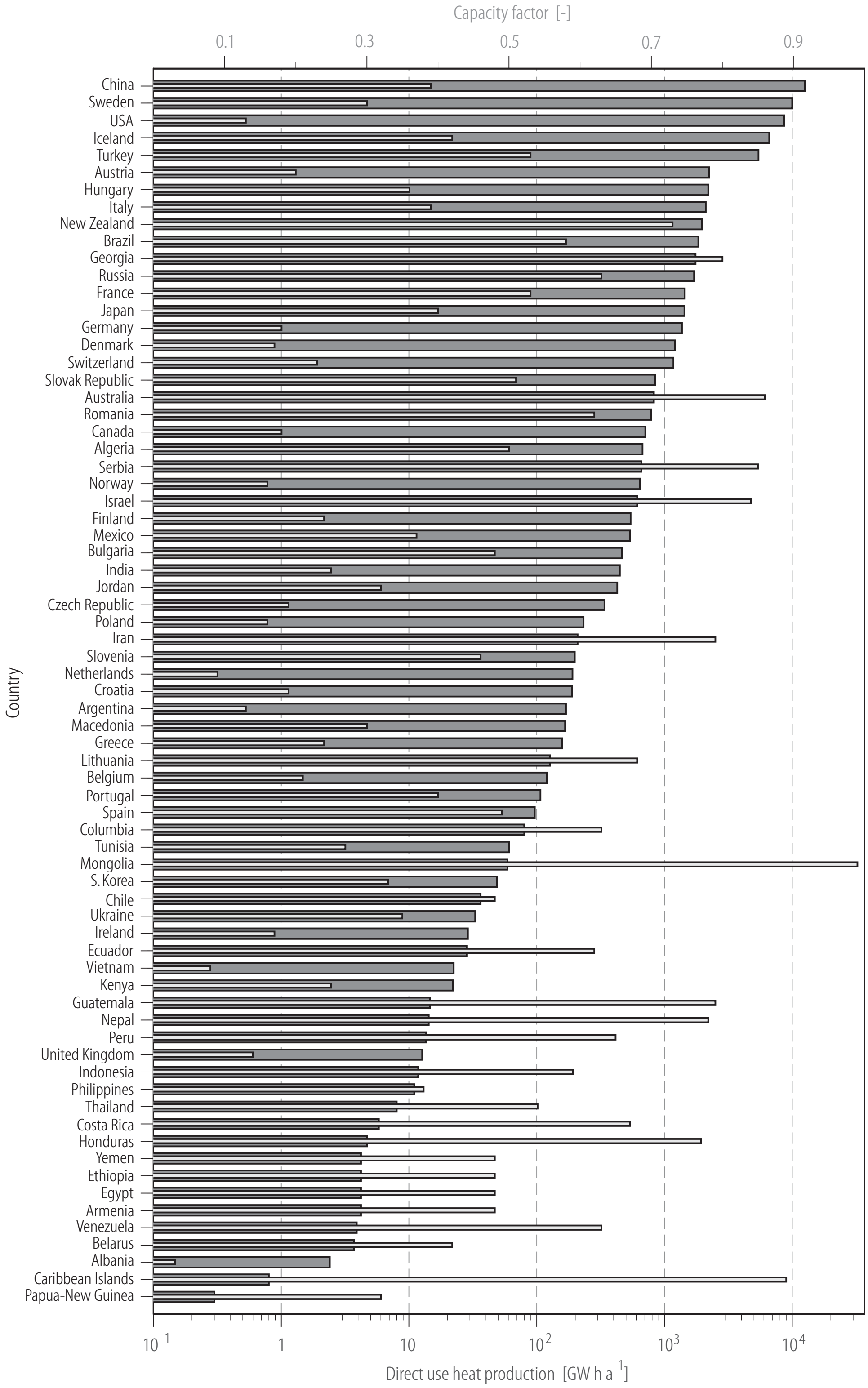

Fig. 8.26. National contributions to the global annual production of about 261 PJ (72.6 TW h) of direct use geothermal heat (big dark bars) and capacity factors (energy produced vs. year-round energy production at full capacity; slim bright bars) by the year 2005. Data: see Table 8.21.

55 countries to the global production of direct use geothermal heat. As direct use is most attractive in moderate to cold climates, the territory of most of these countries lies in this region, at least in part. It is notable that the Peoples Republic of China, a developing and emerging industrial country, is the top producer ahead of the USA, Iceland (where nationwide heat production is almost exclusively geothermal), and a dynamically developing Turkey. More than half of the global direct geothermal heat in the year 2000 was produced in these four countries alone.

The extent to which the available installed geothermal capacity is being used to its full potential is expressed by the capacity factor, the ratio of energy produced per year versus maximum possible annual production. With regard to this capacity factor, Fig. 8.26 and Table 8.20 illustrate that the top five producers of direct use geothermal heat, the People’s Republic of China, Sweden, the USA, Iceland, and Turkey used between just 13% and 53% of the capacity installed in the year 2005. These numbers suggest that an increase in direct use would be possible here without installation of any new capacity. Whether this can be really implemented, however, cannot be predicted without a detailed analysis of the reasons for the comparatively low capacity factors. However, as these five countries comprise 60% of the global direct geothermal heat production, an increased use of their installed capacity would increase the global production significantly. In contrast, in countries with comparatively large capacity factors, a significant increase in direct use geothermal heat production requires new facilities.

Table 8.20. Installed capacity and direct use geothermal heat production in 71 countries (Data: [05Lun]; for Germany: [05Sch] and own calculations, see Table 8.21).

Country	Capacity [MW_t]	Direct Use Heat production		Capacity Factor [-]
		[$TJ\ a^{-1}$]	[$GW\ h\ a^{-1}$]	
Albania	9.6	8.5	2.4	0.03
Algeria	152.3	2417.0	671.4	0.50
Argentina	149.9	609.1	169.2	0.13
Armenia	1.0	15.0	4.2	0.48
Australia	109.5	2968.0	824.5	0.86
Austria	352.0	352.0	2229.9	0.20
Belarus	1.0	13.3	3.7	0.42
Belgium	63.9	431.2	119.8	0.21
Brazil	360.1	6622.4	1839.7	0.58
Bulgaria	109.6	1671.5	464.3	0.48
Canada	461.0	2546.0	707.3	0.18
Caribbean Islands	0.1	2.8	0.8	0.89
Chile	8.7	131.1	36.4	0.48
China	3687.0	45373.0	12604.6	0.39
Columbia	14.4	287.0	79.7	0.63
Costa Rica	1.0	21.0	5.8	0.67
Croatia	114.0	681.7	189.4	0.19
Czech Republic	204.5	1220.0	338.9	0.19
Denmark	821.2	4360.0	1211.2	0.17
Ecuador	5.2	102.4	28.4	0.62
Egypt	1.0	15.0	4.2	0.48
Ethiopia	1.0	15.0	4.2	0.48
Finland	260.0	1950.0	541.7	0.24
France	308.0	5195.7	1443.4	0.53
Georgia	250.0	6307.0	1752.1	0.80
Germany	884.6	4922.0	1368.3	0.18

Country	Capacity [MW_t]	Direct Use Heat production		Capacity Factor [-]
		[$TJ\ a^{-1}$]	[$GW\ h\ a^{-1}$]	
Greece	74.8	567.2	157.6	0.24
Guatemala	2.1	52.5	14.6	0.79
Honduras	0.7	17.0	4.7	0.77
Hungary	694.2	7939.8	2205.7	0.36
Iceland	1791.0	23813.0	6615.3	0.42
India	203.0	1606.3	446.2	0.25
Indonesia	2.3	42.6	11.8	0.59
Iran	30.1	752.3	209.0	0.79
Ireland	20.0	104.1	28.9	0.17
Israel	82.4	2193.0	609.2	0.84
Italy	606.6	7554.0	2098.5	0.39
Japan	413.4	5161.1	1433.8	0.40
Jordan	153.3	1540.0	427.8	0.32
Kenya	10.0	79.1	22.0	0.25
S. Korea	16.9	175.2	48.7	0.33
Lithuania	21.3	458.0	127.2	0.68
Macedonia	62.3	598.6	166.3	0.30
Mexico	164.7	1931.8	536.7	0.37
Mongolia	6.8	213.2	59.2	0.99
Nepal	2.1	51.4	14.3	0.78
Netherlands	253.5	685.0	190.3	0.09
New Zealand	308.1	7086.0	1968.5	0.73
Norway	450.0	2314.0	642.8	0.16
Papua-New Guinea	0.1	1.0	0.3	0.32
Peru	2.4	49.0	13.6	0.65
Philippines	3.3	39.5	11.0	0.38
Poland	170.9	838.3	232.9	0.16
Portugal	30.6	385.3	107.0	0.40
Romania	145.1	2841.0	789.2	0.62
Russia	308.2	6143.5	1706.7	0.63
Serbia	88.8	2375.0	659.8	0.85
Slovak Republic	187.7	3034.0	842.8	0.51
Slovenia	48.6	712.5	197.9	0.46
Spain	22.3	347.2	96.5	0.49
Sweden	3840.0	36000.0	10000.8	0.30
Switzerland	581.6	4229.3	1174.9	0.23
Thailand	1.7	28.7	8.0	0.54
Tunisia	25.4	219.1	60.9	0.27
Turkey	1177.0	19623.1	5451.3	0.53
Ukraine	10.9	118.8	33.0	0.35
United Kingdom	10.2	45.6	12.7	0.14
USA	7817.4	31239.0	8678.2	0.13
Venezuela	0.7	14.0	3.9	0.63
Vietnam	30.7	80.5	22.4	0.08
Yemen	1.0	15.0	4.2	0.48
TOTAL	**27824.8**	**261418.0**	**72621.9**	**0.30**

8.3.1.1 Space heating

In moderate and cold climates most of the national final energy is consumed as heat. As an example, we find that in Germany in the year 2002 about 58% of the national final energy was consumed for space heating, process heat, and hot water (Fig. 8.27). Thus it appears that a huge market should be available for direct use geothermal heat. However, two main obstacles may prevent the use of geothermal heat:

1) In many places heat is available as abundant waste heat, e.g. from thermal power stations. This limits the price that can be obtained on the market. Also, market penetration for geothermal heat may be difficult if the current demand is already satisfied by existing sources.
2) Heat cannot be transported over long distances from the point of production to the end-user unless a grid of well insulated pipelines is in place which can be fed with geothermal heat. Installing a grid exclusively for direct use geothermal heat often turns out to be prohibitively expensive. If, in contrast, heat supply systems are planned for new buildings they can be optimized for direct geothermal use. In these cases geothermal heat may be supplied at a competitive price based on proven and reliable technology: ground-source heat pumps, used primarily for heating (and cooling) of individual buildings, and hydrothermal heating plants for providing heat to municipal district heating systems.

8.3.1.1.1 Earth coupled heat extraction systems

There is variety of different Earth coupled heat extraction systems. All have in common that they extract heat by diffusion only – there is no need to produce groundwater or fluids from deeper reservoirs. There are shallow and deep systems of this kind, consisting of one or several shallow or deep pipe systems in which a heat exchange fluid is circulated which is not in direct contact with the ground or rock. Heat diffuses into these systems across the pipe system from the outside ground or rock [01Dic; 03Lun1].

8.3.1.1.1.1 Horizontal Earth coupled heat exchangers

Horizontal Earth coupled heat exchangers (Fig. 8.28) are pipe systems buried in the ground below the freezing depth. They can be used wherever there is sufficient surface area available for their installation. Therefore they are more rarely installed for space heating and cooling of buildings than vertical borehole heat exchangers.

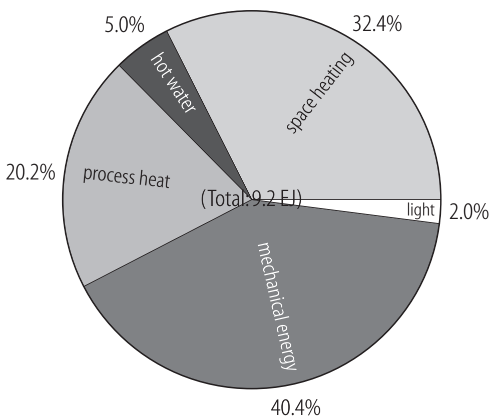

Fig. 8.27. Consumption of final energy in Germany in 2002. Data: [03VDE; 04BMW].

8.3.1.1.1.2 Shallow borehole heat exchangers

Shallow borehole heat exchangers (Fig. 8.29) commonly consist of one or several U-pipes (Fig. 8.30) installed and backfilled in a borehole, the most frequent configuration consisting of two U-pipes arranged at an angle of 90°. Alternatively, coaxial pipe arrangements are also used, but more frequently for deeper boreholes (Fig. 8.30). Shallow borehole heat exchangers are installed in boreholes with depths varying between about 50 m and 250 m. In all shallow systems, heat exchangers extract heat from the isolated primary circulation within the U-pipes or horizontal pipe systems and transmit it into a secondary circuit. As a rule, shallow systems additionally require a heat pump to obtain suitable input temperatures. Depending on the type of domestic heating system, input temperatures vary between about 40 °C and 70 °C for surface heating elements (floor, wall, ceiling) or conventional radiators, respectively. Shallow borehole heat exchangers typically possess a specific power of about 40 W m^{-1} - 55 W m^{-1} ±16 W m^{-1} per unit length [99Kal; 01Ano1; 03Cla2]. The uncertainty of ±30% is primarily due to the natural variability of thermal rock properties, mainly of thermal conductivity or diffusivity.

Since these systems are coupled to a heat pump, they can be used for both heating and cooling of buildings, depending on whether the Earth or the building is the heat source. Cooling buildings with ground-source heat pumps in the summer, while heating the same building with the same systems in winter is becoming increasingly attractive. This can be achieved if heat from the building can be fed into the cooler subsurface during the warm season, i.e. if the underground temperature is lower than that of the fluid circulation. This way, the economical performance of the system may be significantly improved. At the same time, the underground geothermal regime can recover more quickly during the warm season when no heating is required. Heating and cooling with Earth coupled heat pumps requires appropriate large-surface heat distribution systems in the buildings or structures because of the low supply temperature level. Although shallow borehole heat exchangers can be installed in nearly any type of subsurface, soft (sedimentary) rocks are generally more easy (and less expensive) to drill than hard (basement) rocks, from a technical point of view. Also, in porous and fractured rocks heat may flow to the borehole not only by diffusion but also by advection in a regional groundwater flow field. This can improve the thermal yield of a ground-source heat pump significantly.

Fig. 8.28. Horizontal Earth coupled heat exchanger system; yellow box in building basement: heat pump [99Ano1].

Fig. 8.29. Vertical borehole heat exchanger system; yellow box in building basement: heat pump [99Ano1].

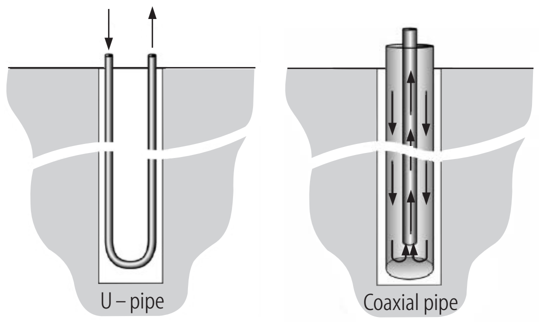

Fig. 8.30. Two common basic pipe arrangements used in borehole heat exchangers [02Geh].

Table 8.21. Top producers of geothermal heat by ground-source heat pumps. Data: [03Lun1; 04Sig2; 04BWP] and own calculations.

Country, Population in Mio.	Number of ground-source heat pumps	Annual heat production [TJ]	Installed power [MW_{th}]	Per capita annual heat production [MJ]
Sweden, 9	200000	28800	2000	3200
USA, 294	500000	13392	3720	46
Germany, 82	51000	4212	780	51
Canada, 32	36000	1080	435	34
Switzerland, 7	27500	2268	420	324
Austria, 8	23000	1332	275	167

Since they do not require any particular thermal anomaly, ground-source heat pumps represent a geothermal heat production technology which is suitable even for regions with altogether ordinary geothermal conditions. This is illustrated by the examples of Sweden, Switzerland, and Austria, three countries without significant geothermal anomalies in cold to moderate climate, but with an impressive annual per capita heat production from ground-source heat pumps (Table 8.21). The corresponding installed thermal power puts Sweden, after Iceland, on rank 2 in the list of per capita installed direct use geothermal power, and Switzerland, Austria, and Germany on ranks 4, 5, and 9.

8.3.1.1.1.3 Heat exchanger piles

Heat exchanger piles (Fig. 8.31) are relatively recent developments: Heat exchanger pipe systems integrated directly into the concrete foundations of buildings and other constructions for heating and cooling. If properly designed and integrated into a combined heating and cooling system right from the beginning, these systems can be a useful part of modern low-energy, low CO_2-emission buildings and constructions. Depending on the size of the buildings or structures, the installed power may range from 10 kW - 800 kW for small houses and large industrial buildings, respectively [02Vua1]. These integrated systems are usually connected to a heat pump. Like for other Earth coupled heat exchangers their specific power depends on the flow rate, the temperature difference between inflow and outflow of the heat exchange fluid (a function of the flow rate as well), the thermal properties of the ground, and the amount of heat advection due to groundwater flow. Depending on local conditions and pile diameters, values reported for specific power per meter of foundation pile range between 20 W m^{-1} and 75 W m^{-1} [04Von2].

Similar types of heat exchangers can also be integrated in other concrete constructions, such as con-

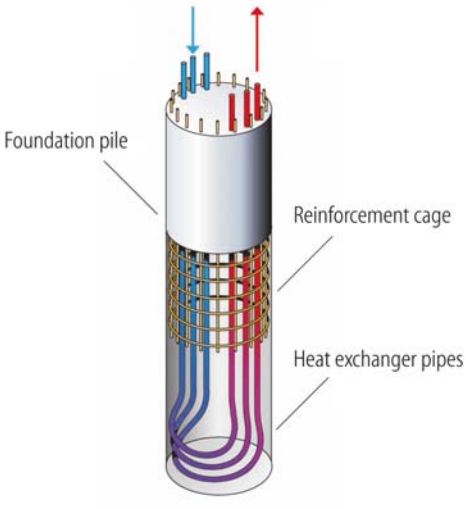

Fig. 8.31. Heat exchanger piles: Earth coupled heat exchanger pipe systems integrated in building foundation piles [04Von2].

crete floors, ceilings and walls. A combined use of these different types of heat exchangers was recently realized in Vienna for heating and cooling of the "Schottenring" subway station [04Von1] where they were integrated in concrete floors and foundation piles. Here, the maximum specific power per square meter of heat exchange surface of all systems exceeds 40 W m^{-2}. The annual average specific power of about 13 W m^{-2} is accordingly lower than this maximum value, corresponding to an average annual heating and cooling energy of about 170 MW h and 120 MW h, respectively. A large new terminal building of the airport in Zürich is heated in winter and cooled in summer using heat exchanger piles integrated in 315 foundation pillars of 30 m length and diameters of 0.9 m - 1.5 m. The associated heating and cooling energy is 470 MW h and 1100 MW h, respectively.

While statistical data on this type of direct use is scarce – for instance 7 MW of installed power are reported for Switzerland by the year 2004 [04Sig2] – its potential is significant. By the end of the year 2002, more than 380 such systems were reported to have been in operation in Austria, Germany, and Switzerland [02Vua1]. Many more applications are conceivable for all kinds of buildings with deep foundations, in particular high-rise buildings and towers, bridges etc. Obviously, an intensified use of these integrated systems for modern low-energy, low-carbon dioxide emission buildings requires both an increased awareness of the available technological options on the part of planners, architects, and developers, and a close cooperation between construction companies and specialists in space heating and cooling systems on the one hand and in Earth coupled heat production systems on the other hand.

8.3.1.1.1.4 Deep borehole heat exchangers

Deep borehole heat exchangers have been installed to depths of about 1500 m - 3000 m and maximum temperatures of about 60 °C - 110 °C [e.g. 99Wet; 02Koh]. In contrast to shallow borehole heat exchangers, U-pipes cannot be used here anymore due to the much greater depth of the boreholes. Instead, these systems consist of a coaxial arrangement of an inner production pipe inserted into an outer borehole casing. Water flows down the annulus of this coaxial system and up again in a central production pipe. In order to minimize heat losses, the production pipe needs to be insulated where the production temperature exceeds the ambient rock temperature. The available operational data from the small number of currently operating deep borehole heat exchangers indicate a specific power of about 20 W m^{-1} - 54 W m^{-1}, similar to that of shallow systems [99Wet; 02Koh]. However, recent studies suggest that currently operating deep borehole heat exchangers may be under-exploiting the available resource significantly [02Koh]: Based on detailed numerical simulations calibrated on operational data from an existing system they conclude that a specific power of at least 85 W m^{-1} can be reached for a system with a depth of 2300 m, corresponding to an installed power of about 200 kW.

As with shallow systems, the heat of the primary circulation within the deep borehole is transferred to a secondary circuit by a heat exchanger. Deep systems often do not require a heat pump due to their higher output temperature. Heat can be fed directly into the building's space heating system or into a local heat distribution system via the heat exchanger. Sometimes, however, a heat pump is used additionally. Without additional shallow boreholes, cooling cannot be provided by most deep borehole heat exchangers: Their elevated production temperatures preclude their use for space cooling.

8.3.1.1.2 Hydrothermal heating systems

Hydrothermal heating systems consist of one or several, usually deep, boreholes for producing (and injecting) water from aquifers or deep reservoirs. Shallow systems are referred to as *groundwater heat pumps* (Fig. 8.32), deep systems as *hydrothermal heating plants* (Fig. 8.33). While there is a variety of different configurations for hydrothermal heating plants, all have in common that hot water or brine is produced and cooled at the surface. Unless it can be further used or discharged into surface waters, the cooled water is injected back into a subsurface reservoir or aquifer. In some countries there are legal thresholds with respect to the permitted heating of the affected aquifer. In the surface unit, heat is extracted from the produced hot water or brine in a heat exchanger and fed into a secondary distribution circuit. Sometimes a heat pump is also switched into the secondary circuit at an appropriate position. In groundwater heat pump installations this is the rule. There are systems which use one single well for fluid production and injection from a deep and into a shallower reservoir, respectively, but most are doublet installations consisting of two boreholes, one for production and one for injection (Fig. 8.32, Fig. 8.33). A sufficient minimum offset between the two well bottoms prevents a thermal short circuit during the installation's life time, commonly 20 years to 30 years. For hydrothermal heating plants, this offset is often on the order of 10^3 m. Frequently the two wellheads are equally offset. However, sometimes it may be attractive or even necessary to drill both boreholes from the same platform and deviate one or both of them.

Fig. 8.32. Groundwater heat pump system; yellow box in building basement: heat pump [99Ano1].

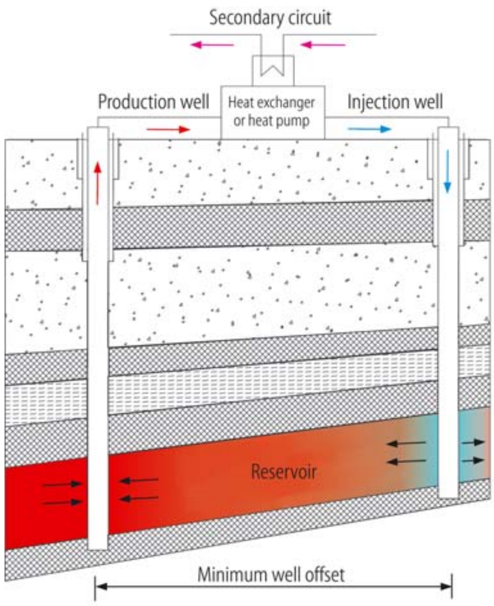

Fig. 8.33. Hydrothermal heating plant, doublet installation (source: Geothermie Neubrandenburg GmbH).

In contrast to conductive heat production by ground-source heat pumps, advective heat production by hydrothermal heating systems requires producing large volumes of hot fluid. Therefore, the most critical properties are hydraulic permeability, reservoir porosity and thickness (see Sect. 8.1.5.3 and Sect. 8.4.1.2; sometimes transmissivity, the product of reservoir thickness and hydraulic conductivity, is used as a lumped property to characterize reservoirs). Accordingly, almost all hydrothermal heating systems are placed in sedimentary rocks, often in sedimentary basins. Sedimentary basins, such as the Pannonian and Paris basins or the Rhine Graben in Europe, frequently display geothermal anomalies (see e.g. [02Hur]). Placing these systems into geothermal anomalies can help to reduce the drilling depth to the desired temperature, usually ranging from about 60 °C - 100 °C for these low enthalpy heat production systems (cf. Table 8.19). A reduced drilling depth can be crucial for the economic feasibility of hydrothermal heating plants as drilling cost amounts to at least half of the final turnkey investment cost [99Kay] (see also Sect. 8.4.1.2).

8.3.1.2 Commercial and industrial applications

Direct use geothermal energy may be both cost effective and reliable in industrial applications. Some industries use steam or superheated water, while agriculture and aquaculture require lower temperature geothermal fluids. At present, the largest industrial applications are in pulp, paper and wood processing. Examples include timber processing in New Zealand, a diatomaceous earth plant in Iceland, a vegetable dehydration plant in the United States, and industrial water in Romania [04WOB]. Other applications currently operating or studied for feasibility include [92Ste1; 00Rag; 01Fri; 01Lun; 02Bar; 03Lie; 03Lun2; 03Raf2; 04WOB]:

- Hydrogen production by high-temperature steam hydrolysis operating at 800 °C - 1000 °C;
- Hot-dip galvanizing of metals (a chemical process used to coat steel or iron with zinc by passing the steel through a molten bath of zinc at a temperature of around 450 °C);
- Diatomite (kieselguhr) production (requiring steam for heating and drying);
- Salt production from seawater (requiring steam for evaporation and drying);
- Timber drying;
- Seaweed and kelp processing (requiring hot water at about 110 °C);
- Fat-liquoring[2] and drying in the tanning process of leather (usually performed at temperatures of 60 °C - 66 °C)
- Thermal distillation desalination driven by low enthalpy (52 °C - 76 °C) geothermal resources;
- Geothermal water (48 °C - 79 °C) used for washing in wool mills and for dyeing cloth;
- Production of chemicals as a by-product of heat production from geothermal brines.

Next to process heat, direct use geothermal heat is also successfully used for [03Pop2; 03Raf1]

- heating of swimming pools;
- heating of greenhouses;
- heating of fish and turtle aquaculture pools to increase productivity;
- melting of snow and ice on sports fields, bridges, and roads;
- air conditioning and refrigeration by absorption or adsorption cooling.

Table 8.22 summarizes a variety of geothermal direct use applications and the associated temperatures. In applications which require high conversion efficiencies to reach economic feasibility, the concept of cascaded use has been introduced, i.e. the serial connection of several direct use applications on successively lower temperature levels. This way the resource can be exploited much more effectively and therefore the efficiency can be increased significantly.

To what extent these commercial and industrial applications can contribute to the national energy supply may be illustrated using the example of Iceland. There geothermal energy provides 50% of the coun-

[2]) Fat-liquoring is introducing oil into the skin prior to drying to replace the natural oils lost during processing.

try's annual primary energy consumption of about 120 PJ, corresponding to 434 GJ per capita – higher than in any other country [00Rag]. A total of 20 PJ, nearly 17% of this energy, is provided by direct use geothermal heat. While about ¾ of this are consumed for space heating, the remaining ¼ is used in industrial and commercial applications. Traditionally, their energy demand would have been satisfied by fossil fuels. Therefore, substituting these with direct use geothermal heat helps not only to reduce the need to import hydrocarbons, but also to reduce the emission of the greenhouse gas carbon dioxide to the atmosphere.

Table 8.22. Commercial and industrial applications of geothermal direct use and associated temperatures [02Bar; 04WOB].

Temperature T [°C]	Process
180	evaporation of highly concentrated solutions
	refrigeration by ammonia absorption
	digestion in paper pulp
170	heavy water via hydrogen sulfide process
	drying of diatomaceous earth
	digestion of paper pulp
160	drying of fish meal
	drying of timber
150	alumina via Bayer's process
140	drying farm products at high rates
	canning of food
130	evaporation in sugar refining
	extraction of salts by evaporation and crystallization
	fresh water by distillation
120	most multi-effect evaporation
	concentration of saline solution
110	drying and curing of light aggregate cement slabs
100	drying of organic materials (seaweed, grass, vegetables, etc.)
	washing and drying of wool
90	drying of stock fish
	intense de-icing operations
80	space-heating (buildings and greenhouses)
70	refrigeration (lower temperature limit)
60	animal husbandry
	greenhouses by combined space and hotbed heating
50	mushroom growing
	balneology
40	soil warming
	swimming pools, biodegradation. fermentations
30	warm water for year-round mining in cold climates
	de-icing
	hatching of fish or turtles
20	fish farming

8.3.2 Power generation

Geothermal power generation requires vapor to drive turbines. It can be derived as either wet or dry steam from natural reservoirs. In absence of natural steam reservoirs, steam can be also generated in hot dry rock (HDR) or enhanced geothermal systems (EGS) engineered in the subsurface. At a lower temperature level, vapor for driving turbines can be obtained alternatively by evaporating fluids with a lower boiling point than water. This process is known as Organic Rankine Cycle (ORC) because initially it involved organic compounds, such as toluol (C_7H_8), pentane (C_5H_{12}), propane (C_3H_8), or halogenated hydrocarbons. More recently, the so-called Kalina Cycle technology [84Kal; 89Wal] improves the efficiency of this process further by evaporating a mixture of water and ammonia (NH_3) over a finite temperature range rather than a pure fluid at a definite boiling point (see also Sect. 8.4.2.2).

Wet and dry steam reservoirs are water and vapor dominated, respectively (Table 8.19). Wet steam fields contain pressurized water at temperatures above 100 °C and a smaller amount of steam in the shallower, lower-pressure parts of the reservoir. Hot, pressurized water is the dominant phase inside the reservoir. Vapor dominated, dry steam fields produce dry saturated or slightly super-heated steam at pressures above atmospheric. This steam has the highest enthalpy (energy content), generally close to 2.8 MJ kg^{-1}. Dry steam fields are less common than wet steam fields, but about half of the geothermal electric energy produced worldwide is generated in the six vapor dominated fields at Lardarello and Monte Amiata in *Italy*; The Geysers (California) in the *USA*; Matsukawa in *Japan*; and Kamojang and Darajat in *Indonesia* [02Bar].

Examples of electric power producing wet steam fields are: Cerro Prieto, Los Azufres, and Los Humeros in *Mexico*; Momotombo in *Nicaragua*; Ahuachapán-Chipilapa in *El Salvador*; Miravalles in *Costa Rica*; Zunil in *Guatemala*; Wairakei, Ohaki, and Kawerau in *New Zealand*; Salton Sea, Coso, and Casa Diablo (California), Puna (Hawaii), Soda Lake, Steamboat Springs, and Brady Hot Springs (Nevada); and Cove Fort (Utah) in the *USA*; Dieng and Salak in *Indonesia*; Mak-Ban, Tiwi, Tongonan, Palinpinon, and Bac Man in the *Philippines*; Pauzhetskaya and Mutnovsky in *Russia*; Fang in *Thailand*; Kakkonda, Hatchobaru, and Mori in *Japan*; Olkaria in *Kenya*; Krafla in *Iceland*; Azores in *Portugal*; Kizildere in *Turkey*; Latera in *Italy*; Milos in *Greece*.

While geothermal power has been produced for a century, its development has been rather slow in the first half of this period: The first geothermal power plant was commissioned in 1913 in Larderello, Italy with an installed capacity of 250 kW_e. Only about half a century later the next geothermal power plants were commissioned at Wairakei, New Zealand in 1958, an experimental plant at Pathe, Mexico in 1959, and The Geysers in the USA in 1960. Today, the Tuscan region around Lardarello is still the center of the Italian geothermal power production with an installed capacity of about 790 MW_e and a production of 5340 GW h_e in the year 2003 [05Ber]. But new centers have emerged since, in particular in Asia and Central America (Table 8.23), so that by the year 2005 the total global installed capacity for geothermal electric energy production had reached a level of 8912 MW_e [05Ber]. While this is just about the equivalent of 9 to 15 nuclear or large thermal power stations, the growth of geothermal power has been steady over the last decade at an impressive rate of 24% or roughly 2.5% per year. Figure 8.34 shows the capacity for geothermal electric energy production installed in 24 countries world-wide. The top two countries in this list, the USA and the Philippines, represent already half of the total installed capacity, the next three, Mexico, Indonesia, and Italy, another 29% (see also Table 8.23).

In contrast to direct use, electric power production is not concentrated in countries of moderate to cold climates, but follows the availability of natural steam reservoirs. The next six countries on this list, Japan, New Zealand, Iceland, Costa Rica, El Salvador, and Kenya, contribute another 17% to the global total installed capacity. The following 13 countries with less than 100 MW_e installed capacity each make up the remaining 4%. However, Fig. 8.34 clearly shows that geothermal power production will become ever important both in some of the most important emerging economies, such as the Philippines, Mexico, and Indonesia, and in developing countries such as El Salvador, Costa Rica, Nicaragua, and Kenya. In developed countries as well, such as Iceland, New Zealand, Italy, and the USA, geothermal production of electric energy has reached and maintained a level between 16% and 0.5% relative to the total national production (Fig. 8.35 and Table 8.23). Remarkable increases of 244% and 18 % have been achieved since the year 2000 in Russia and Kenya, respectively, if only from an admittedly low level [05Ber].

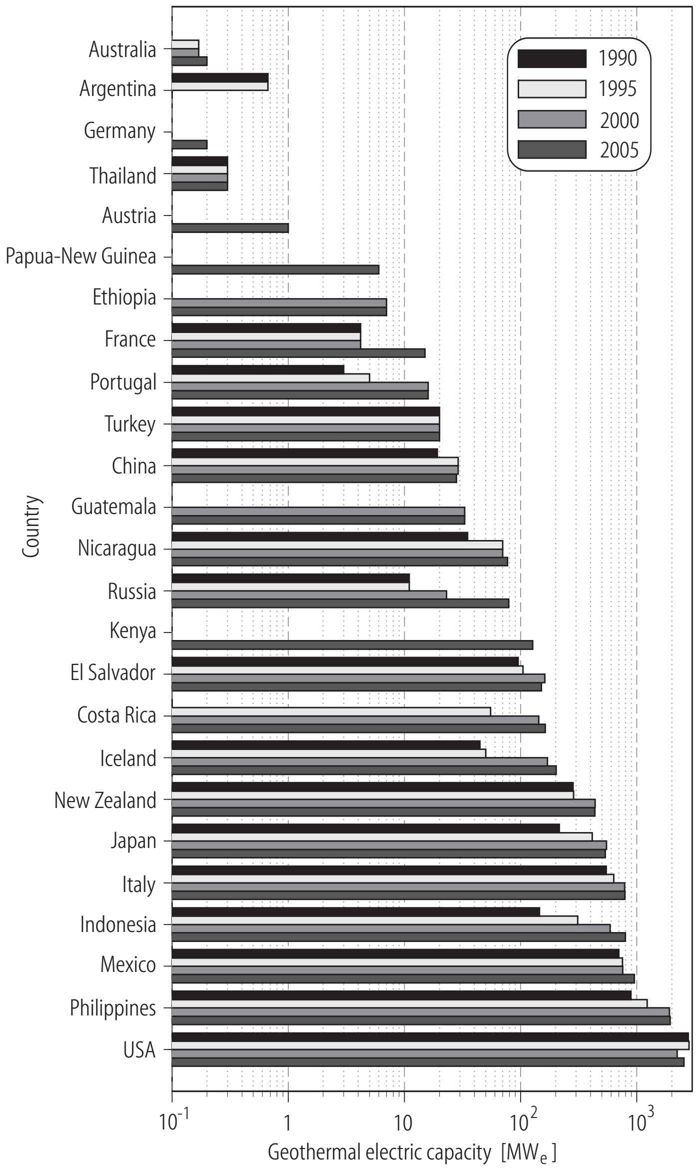

Fig. 8.34. Geothermal electric capacity installed worldwide in the years 1990-2005 (see Table 8.23). Data: [05Ber].

In emerging economies and developing countries geothermal electric power production is boosting the industrial development already today. Figure 8.35 shows the geothermal contributions to the production of electric energy and the installed capacity for electric energy production [05Ber] by the year 2005 for the same 24 countries as in Fig. 8.34: Here, Iceland is the only developed country among the top five with respect to both criteria, the others being developing or emerging economies. In these five countries, more than 10% of the produced electricity is geothermal. It cannot be over-estimated how beneficial an increased independence from imported hydrocarbons is on the national budgets of developing or emerging economies in countries which are in general not among the oil or gas producers. Additionally, due to low emission of greenhouse gases during geothermal energy production, geothermal electric energy is a serious alternative to consider with respect to a reduction of greenhouse-gas emissions to the atmosphere (see Sect. 8.4.2.4.3 for more details).

The HDR technology has been developed since the early 1970s in the US, Japan, France, Germany, the UK, and Sweden [99Abe]. While current HDR research projects in Europe and Japan are being transformed into commercial demonstration installations, commercial projects are under way in Australia. In contrast to preceding scientific experimentation and demonstration installations, this new phase involves local and international power producers at a significant level. Although at present no HDR-produced electricity is marketed yet, several commercial HDR installations are currently being planned and drilled, for instance in the Central European Rhine Graben and in Australia. They are expected to start producing electric power with an installed capacity of 3 MW -15 MW within the period 2005-2010 [99Ano2; 02Vua2; 03Ano1; 03Ano3]. If successful, this technology has a great potential for producing geothermal electric energy in regions without natural steam reservoirs.

Table 8.23. Geothermal electric capacity and energy production in 24 countries, as well as corresponding fractions of the total national capacity and energy production, and the world geothermal electric capacity and energy production of 8912 MW_e and 56.8 TW h (204.5 PJ), respectively, in 2005. Data: [05Ber].

Country	Installed capacity [MW]	Running capacity [MW]	Energy produced [$GWha^{-1}$]	Number of units	National capacity [%]	World capacity [%]	National energy [%]	World energy [%]
Australia	0.2	0.1	0.5	1	negligible	negligible	negligible	0.001
Austria	1	1	3.2	2	negligible	negligible	negligible	0.006
China (Tibet)	28	19	95.7	13	30.0	0.314	30.0	0.168
Costa Rica [1])	163	163	1145.0	5	8.4 [1])	1.829 [2])	15.0 [1])	2.016 [2])
El Salvador [1])	151	119	967.0	5	14.0 [1])	1.694 [2])	24.0 [1])	1.703 [2])
Ethiopia	7	7	–	1	1.0	0.078	–	–
France (Guadeloupe Island)	15	15	102.0	2	9.0	0.168	9.0	0.180
Germany	0.2	0.2	1.5	1	negligible	negligible	negligible	0.003
Guatemala [1])	33	29	212.0	8	1.7 [1])	0.370	3.0 [1])	0.373
Iceland [1])	202	202	1406.0	19	13.7 [1])	2.267 [2])	16.0 [1])	2.475 [2])
Indonesia [1])	797	838	6085.0	15	2.2 [1])	8.943 [2])	6.7 [1])	10.713 [2])
Italy [1])	790	699	5340.0	32	1.0 [1])	8.864 [2])	1.9 [1])	9.402 [2])
Japan	535	530	3467.0	19	0.2	6.003 [2])	0.3	6.104 [2])
Kenya [1])	127	127	1088.0	8	11.2 [1])	1.425 [2])	19.0 [1])	1.916 [2])
Mexico [1])	953	953	6282.0	36	2.2 [1])	10.693 [2])	3.1 [1])	11.060 [2])
New Zealand [1])	435	403	2774.0	33	5.5 [1])	4.881 [2])	7.1 [1])	4.884 [2])
Nicaragua [1])	77	38	270.7	3	11.2 [1])	0.864	9.8 [1])	0.477
Papua-New Guinea (Lihir Isl.)	6	6	17.0	1	10.9	0.067	–	0.0299
Philippines [1])	1931	1838	9419.0	57	12.7 [1])	21.667 [2])	19.1 [1])	16.58 [2])
Portugal (San Miguel Island)	16	13	90.0	5	25.0	0.179	–	0.158
Russia	79	79	85.0	11	negligible	0.886	negligible	0.150
Thailand	0.3	0.3	1.8	1	negligible	0.003	negligible	0.003
Turkey	20	18	105.0	1	negligible	0.224	negligible	0.185
USA	2544	1914	17840.0	189	0.3	28.546 [2])	0.5	31.410 [2])
Total	8912	8010	56798.0	468	–	100.000	–	100.000

[1]) Major contributions to national capacity and energy.
[2]) Major contributions to world capacity and energy.

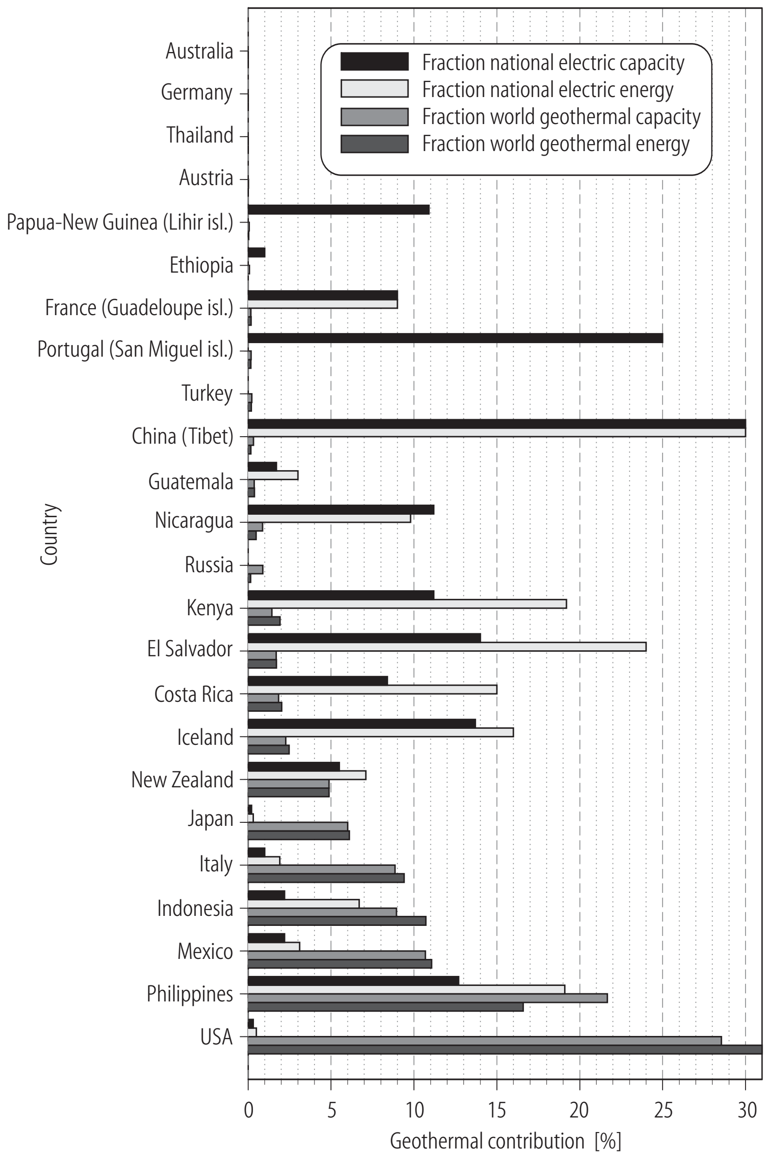

Fig. 8.35. Geothermal contribution to the national electric capacity and the electric energy production of 24 countries; National contributions to the world geothermal electric capacity of 8912 MW_e and the world geothermal energy production of 56800 MW h by the year 2005 (see Table 8.23). Data: [05Ber].

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