CHAPTER 14

Geothermal energy

CONTENTS

LEARNING AIMS

- Identify the source of geothermal energy and appreciate issues around its sustainability.
- Identify requirements for geothermal energy to be potentially useful for electricity generation and understand why suitable locations are geographically restricted.
- Appreciate potential for more geographically widespread use of geothermal energy for thermal applications.
- Understand operating principles of ground-source heat pumps.

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§14.1 INTRODUCTION

The inner core of the Earth reaches a maximum temperature of about 4000°C, with the outward heat flow maintained predominantly by natural radioactive decay of certain dispersed elements (e.g. uranium, thorium and certain isotopes of potassium). Heat passes out through the solid submarine and land surface mostly by conduction – geothermal heat – and occasionally by active convective currents of molten magma or heated water. The average geothermal heat flow at the Earth's surface is only 0.06 W/m^2, with average temperature gradient of 25 to 30°C/km. This continuous heat current is trivial compared with other renewable supplies in the above surface environment that in total average about 500 W/m^2 (see Fig. 1.2). However, at certain specific locations increased temperature gradients occur, indicating significant geothermal resources. Regions of geothermal potential generally have permeable rock of area ~10 sq km and depth ~5 km through which water may circulate. Consequently, they can be harnessed at fluxes of 10 to 20 W/m^2 to produce ~100 MW (thermal) per km^2 in commercial supplies for at least 20 years of operation. Regions of 'hot, dry rock' have to be fractured artificially to become permeable, so that water may be circulated through the fractures to extract the heat.

There are three main *uses* of geothermal energy, as listed below in the order of *decreasing thermodynamic quality*, which happens also to be the order of their *increasing geographical availability*.

1. *Electricity generation.* At a few locations geothermal heat is available at temperatures of more than 150°C, as a natural flow of high-pressure water and/or steam, so having the potential for electrical power production from turbines. Several geothermal electric power

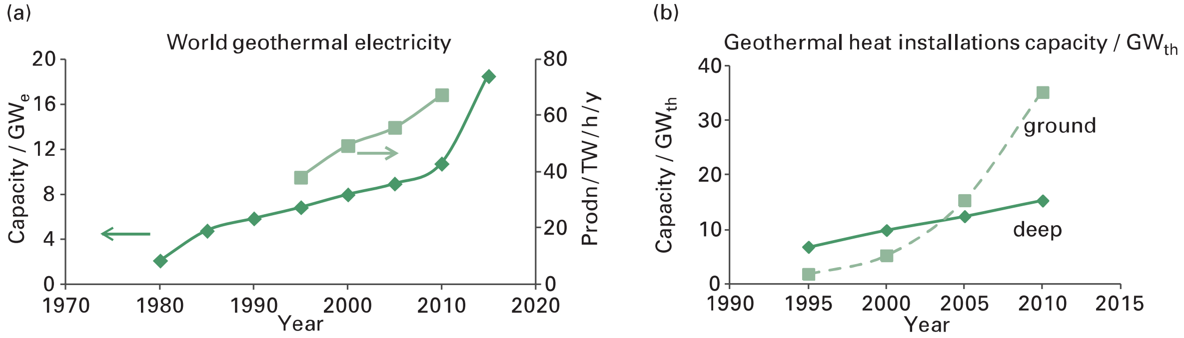


Fig. 14.1

Growth in world geothermal installations.

a Heat to electricity; electrical generation capacity (GW$_e$) (left axis) and annual electricity generation (TWh) (right axis); capacity in 2015 is estimated from announced plans.

b Heat use only: installed capacity (GW$_{th}$) drawing on 'deep heat' (solid curve) and on 'ground heat' (dashed curve).

Source: data from WGC(2010).

complexes have operated for many years, especially in Italy, Iceland, New Zealand and the USA (see Fig. 14.2). The number of similar installations has increased steadily since the 1970s (Fig 14.1(a)). As for hydropower, hydrothermal power technology is mature and long-lasting when tailored to specific sites. The power may be used constantly for baseload at a cheap per unit cost. New developments have increased rapidly in the relatively unexploited geothermally active regions of the Philippines, Indonesia and western USA (see Table 14.1).

2 *Hot water supply.* In many more locations, geothermal heat is available at ~50 to 70°C; for instance, for 'medicinal' bathhouses in the Roman Empire, and today for greenhouse heating for vegetable crops and soft fruits, for crop drying, for aquaculture of fish and algae, for district heating servicing buildings and for industrial process heat (e.g. for paper pulp from wood processing, and for leaching chemicals). More than 60 countries list such uses, many of which do not produce geothermal electricity (see Table 14.1 and Fig. 14.1(b)).

3 *Heat pumps.* Heat at ambient temperature from *near-surface* ground (to depths of usually about 3 m), or from rivers and lakes, is input to electrical-powered heat pumps, which provide heat to buildings at increased temperature. The systems are often called 'geothermal', although the input heat arises from soil heated by sunshine and ambient air. Note that ground at depths of more than about 2 m has

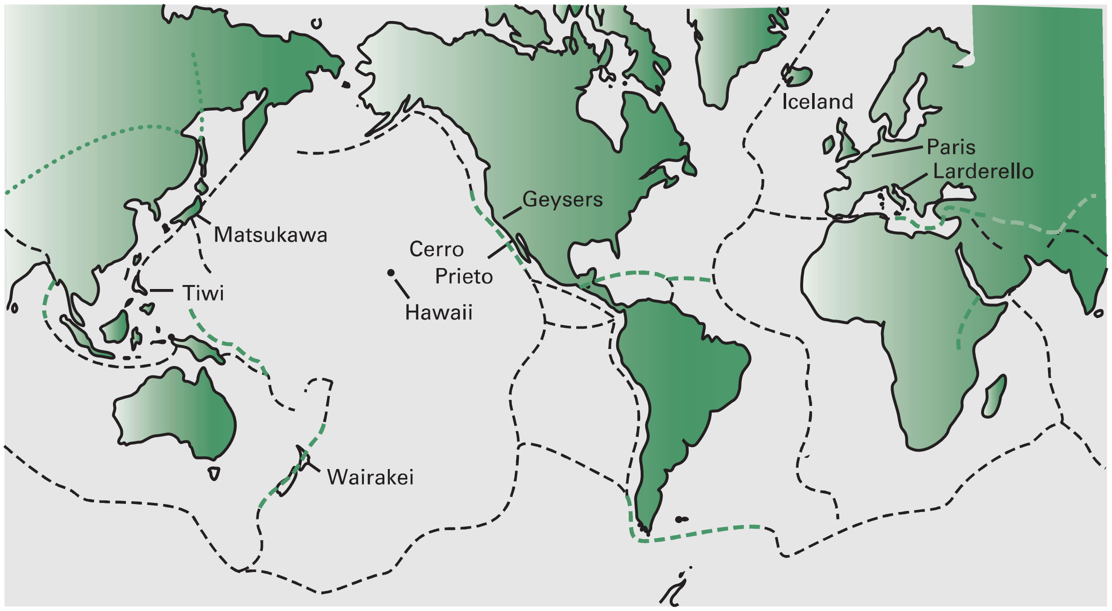


Fig. 14.2

Key named regions harnessing geothermal energy for heat production and/or electricity generation. Dashed lines indicate plate boundaries. Colored lines indicate areas of extra strain.

Table 14.1 *Countries with significant use of geothermal energy.* **Table shows installed capacity for electricity generation ($\mathrm{MW_e}$), capacity factor Z for geothermal electricity, and installed capacity for direct heat use (excluding 'surface' ground- and air-sourced heat pumps) ($\mathrm{MW_{th}}$). All data are for 2010.**

Country	*Electricity capacity* MW_e	*% of world geothermal total*	*Electricity capacity factor Z* *(%)*	*Direct heating capacity (excluding heat pumps)* *(MW_{th})*	*% of world total of direct heating*
USA	3093	29	61	611	4
Philippines	1904	18	62	3	
Indonesia	1197	11	92	2	
Mexico	958	9	84	155	1
Italy	843	8	75	636	4
New Zealand	628	6	74	386	3
Iceland	575	5	91	1822	12
Japan	536	5	65	2093	14
El Salvador	204	2	79	2	
Kenya	167	2	98	16	
Costa Rica	166	2	78	1	
Nicaragua	88	1	40	0	
Turkey	82	1	68	1548	10
Russia	82	1	61	307	2
China	24		71	3690	24
others	168	2		4075	27
WORLD TOTAL	**10715**	**100%**		**15347**	**100%**

Source: Bertani (2010), Lund *et al.* (2010).

nearly constant temperature through the year. In reverse mode extracting heat from buildings, the same heat pumps may be used for cooling, i.e. they function as refrigerators. This technology is available worldwide and is by far the most rapidly growing 'geothermal' application (Fig. 14.1(b)). The relevant technology is outlined in §14.5.

In Chapter 1, renewable energy was defined as '*energy obtained from naturally repetitive and persistent flows of energy occurring in the local environment*'. By this definition, most supplies of geothermal energy may be classed as renewable, because the energy would otherwise be dissipated continuously in the local environment (e.g. from hot springs or geysers). In other geothermal supply, the current of heat is increased artificially (e.g. by fracturing and actively cooling 'hot' rocks, which remain in place, but do not reheat except over the very long term, so the resource in practice has a finite lifetime). Such enhanced geothermal systems (EGS) definitely have the potential to supply energy without mining and extraction of materials, so 'hot rocks' technology is being researched and developed as a means of alternative energy (§14.4.3).

§14.2 GEOPHYSICS

Sections through the Earth are shown in Fig. 14.3. Heat transfer from the semi-fluid mantle maintains a temperature difference across the relatively thin crust of 1000°C, and a mean temperature gradient of ~30°C/km. The crust solid material has a mean density ~2700 kg/m^3, specific heat capacity ~1000 $J\,kg^{-1}\,K^{-1}$ and thermal conductivity ~2 $W\,m^{-1}\,K^{-1}$. Therefore the average upward geothermal flux is ~0.06 W/m^2, with the heat stored in the crust globally at temperatures greater than surface temperature being ~10^{20} J/km^2. If just 0.1% of this heat were to be 'extracted' over 30 years, the heat power available would be 100 MW/km^2. Such heat extraction from the rocks would be replenished in the very long term, eons after the artificial heat extraction stopped. These calculations give the order of magnitude of the quantities involved and show that geothermal sources are a large potential energy supply.

Heat passes outward from the crust by (1) natural cooling and friction from the core; (2) radioactive decay of elements; and (3) chemical reactions. The time constants of such processes over the whole Earth are so long that it is not possible to know whether the Earth's temperature is presently increasing or decreasing. The radioactive elements are concentrated in the crust by fractional recrystallization from molten material, and are particularly pronounced in granite. However, the production of heat by radioactivity or chemical action is only significant over many millions of years (see Problem 14.2). Consequently geothermal heat supplies from engineered extraction (as distinct from hot springs) relies on removing stored heat in the thermal capacity of solid material and water in the crust, rather than on replenishment. If conduction through uniform material were the only geothermal heat transfer mechanism, the temperature gradient through the whole crust would be constant.

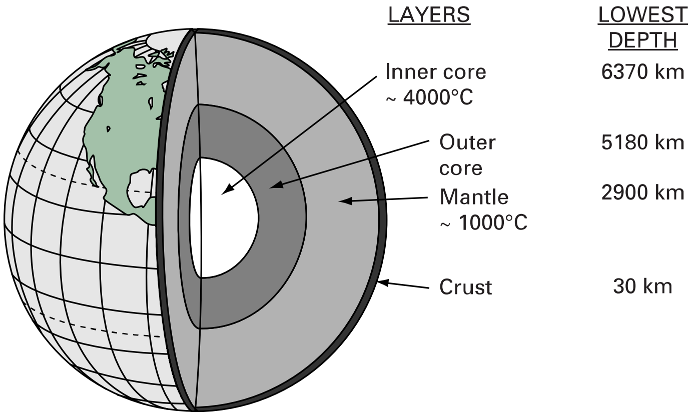


Fig. 14.3

Geothermal structure of the Earth, showing average lower depths of named layers. The crust has significant variation in composition and thickness over a local scale of several kilometres.

However, if convection occurs 'locally', as from water movement, or if local radioactive or exothermic chemical heat sources occur, there are anomalous temperature gradients within the Crust.

On a global perspective, the Earth's Crust consists of large plates (Fig. 14.2). At the plate boundaries there is active convective thermal contact with the Mantle, evidenced by seismic activity, volcanoes, geysers, fumaroles and hot springs – the so-called 'ring of fire'. The geothermal energy potential of these regions is very great, owing to increased anomalous temperature gradients (to ~100°C/km) and to active release of water as steam or superheated liquid, often at considerable pressure when tapped by drilling. Therefore it is no coincidence that each of the eight largest producers of geothermal electricity have experienced locally a major earthquake and/or volcanic eruption in the past 100 years (i.e. 'now' in geological terms).

Moderate increases in temperature gradient to ~50°C/km occur in localized regions away from plate boundaries, owing to anomalies in crust composition and structure. Heat may be released from such regions naturally by deep penetration of water in aquifers and subsequent convective water flow. The resulting hot springs, with increased concentrations of dissolved chemicals, are often famous as health spas. 'Deep' aquifers are today tapped by drilling to depths of ~5 km or less, so providing sources of heat at temperatures from ~50 to ~200°C. If the anomaly is associated with material of small thermal conductivity (i.e. dry rock), then a 'larger than usual' temperature gradient occurs with a related increase in stored heat.

Geothermal information has been obtained from mining, oil exploration and geological surveys; therefore, some geothermal information is available for most countries. The most important parameter is temperature gradient; accurate measurements depend on leaving the drill hole undisturbed for many weeks so that temperature equilibrium is re-established after drilling. Deep-drilled *survey wells* commonly reach depths of 6 km, and the technology is available to drill to 15 km or more. The large cost of these survey wells is partly why the suspected high-grade geothermal potential of many developing countries has not yet been properly explored; lower grade heat does not require such detailed assessment before it can be exploited. The principal components of a geothermal energy plant are the boreholes, so heat extraction from depths to 15 km may be contrived eventually.

There are three classes of global geothermal regions:

1. *Hyperthermal*: Temperature gradient ≥80°C/km. These regions are usually on tectonic plate boundaries. The first such region to be tapped for electricity generation was in 1904 at Larderello in Tuscany, Italy. Nearly all geothermal power stations are in such areas.
2. *Semithermal*: Temperature gradient ~40°C/km to 80°C/km. Such regions are associated generally with anomalies away from plate

boundaries. Heat extraction is from harnessing natural aquifers or fracturing dry rock. A well-known example is the geothermal district heating system for houses in Paris.

3. *Normal*: Temperature gradient <40°C/km. These remaining regions are associated with average geothermal conductive heat flow at ~0.06 W/m^2. It is unlikely that these areas can ever supply geothermal heat at prices competitive to present (finite) or future (other renewable) energy supplies.

In each class it is, in principle, possible for heat to be obtained by the following:

1. *Natural hydrothermal circulation,* in which water percolates to deep aquifers to be heated to dry steam, vapor/liquid mixtures, or hot water. Emissions of each type may be observed in nature. If pressure increases by steam formation at deep levels, spectacular geysers may occur, as at the geysers near Sacramento in California and in the Wairakei area near Rotorua in New Zealand (see Fig. 14.5(b)). Note, however, that liquid water is ejected, and not steam.
2. *Hot igneous systems* associated with heat from semi-molten magma that solidifies to lava. The first power plant using this source was the 3 MW$_e$ station in Hawaii, completed in 1982.
3. *Dry rock fracturing.* Poorly conducting dry rock (e.g. granite) stores heat over millions of years with a subsequent increase in temperature. Artificial fracturing from boreholes enables water to be pumped through the rock, so that (in principle) the heat can be extracted. However, there are many practical difficulties with this, as discussed in §14.4.3.

In practice, geothermal energy plants in *hyperthermal* regions are associated with natural hydrothermal systems; in *semithermal* regions both hydrothermal and (perhaps) hot rock extraction may be developed; *normal* areas have too small a temperature gradient for commercial interest, except for near-surface heat pumps.

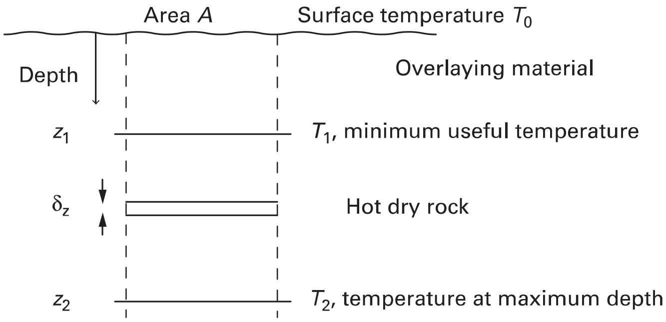


Fig. 14.4

Profile of hot dry rock system for calculating the heat content of the resource (see §14.3.1).

§14.3 DRY ROCK AND HOT AQUIFER ANALYSIS

§14.3.1 Dry rock: algebra to calculate potential heat output

We consider a large mass of dry material extending from near the Earth's surface to deep inside the crust (Fig. 14.4). The rock has density ρ_r, specific heat capacity c_r and cross-section A. Surface temperature is T_0. With uniform material and no convection, G is the rate of linear increase of temperature T with depth z. If z increases *downward* from the surface at $z = 0$,

$$T = T_0 + \frac{\mathrm{d}T}{\mathrm{d}z} z = T_0 + Gz \tag{14.1}$$

If the minimum useful temperature is T_1 at depth z_1, then

$$T_1 = T_0 + Gz_1; \quad \textit{and} \quad z_1 = (T_1 - T_0) / G \tag{14.2}$$

The useful heat content δE, at temperature T (> T_1), in an element of thickness δz at depth z is:

$$\delta E = (\rho_r A \delta z) c_r (T - T_1) = (\rho_r A \delta z) c_r G (z - z_1) \tag{14.3}$$

The total useful heat content of the rock to depth z_2 becomes:

$$\begin{aligned} E_0 &= \int_{z=z_1}^{z_2} \rho_r A c_r G (z - z_1)\, dz \\ &= \rho_r A c_r G \left[\frac{z^2}{2} - z_1 z \right]_{z_1}^{z_2} = \rho_r A c_r G \left[\left(\frac{z_2^2}{2} - z_1 z_2 \right) - \left(\frac{z_1^2}{2} - z_1^2 \right) \right] \\ &= \frac{\rho_r A c_r G}{2} (z_2^2 - 2 z_1 z_2 + z_1^2) = \frac{\rho_r A c_r G}{2} (z_2 - z_1)^2 \end{aligned} \tag{14.4}$$

Alternatively, let the average available temperature greater than the minimum T_1 be θ:

$$\theta = (T_2 - T_1) / 2 = \frac{G(z_2 - z_1)}{2} \tag{14.5}$$

then:

$$E_0 = C_r \theta = \frac{C_t G (z_2 - z_1)}{2} \tag{14.6}$$

where C_r is the total thermal capacity of the rock between z_1 and z_2,

$$C_r = \rho_r A c_r (z_2 - z_1) \tag{14.7}$$

so substituting for C_r in (14.6), $E_0 = \dfrac{\rho_r A c_r G (z_2 - z_1)^2}{2}$ (14.8)
as in (14.4).

Assume heat is extracted from the rock uniformly in proportion to the temperature excess over T_1 by a flow of water with volume flow rate $\dot{V}$, density ρ_w, specific heat capacity c_w. The water is heated from T_0 through a temperature difference θ. Assuming a perfect heat exchanger, then the rock of thermal capacity C_r will cool by an equal temperature change, i.e.

$$\dot{V} \rho_w c_w \theta = -\mathrm{C}_r \frac{\mathrm{d}\theta}{\mathrm{d}t} \tag{14.9}$$

$$\frac{\mathrm{d}\theta}{\theta} = -\frac{\dot{V} \rho_w c_w}{\mathrm{C}_r} \mathrm{d}t = -\frac{\mathrm{d}t}{\tau} \tag{14.10}$$

so $\theta = \theta_0 \exp(-t / \tau)$ (14.11) where the rock cools with a time constant τ given by

$$\tau = \frac{C_r}{\dot{V}\rho_w c_w} \tag{14.12}$$

Substituting for C_t from

$$\tau = \frac{\rho_r A c_r (z_2 - z_1)}{\dot{V}\rho_w c_w} \tag{14.13}$$

The useful heat content $E = C_r\theta$, so

$$E = E_0 e^{-t/\tau} \equiv E_0 \exp(-t/\tau) \tag{14.14}$$

and the rate of heat extraction steadily decreases as

$$\frac{dE}{dt} = \frac{E_0}{\tau}\exp(-t/\tau) \tag{14.15}$$

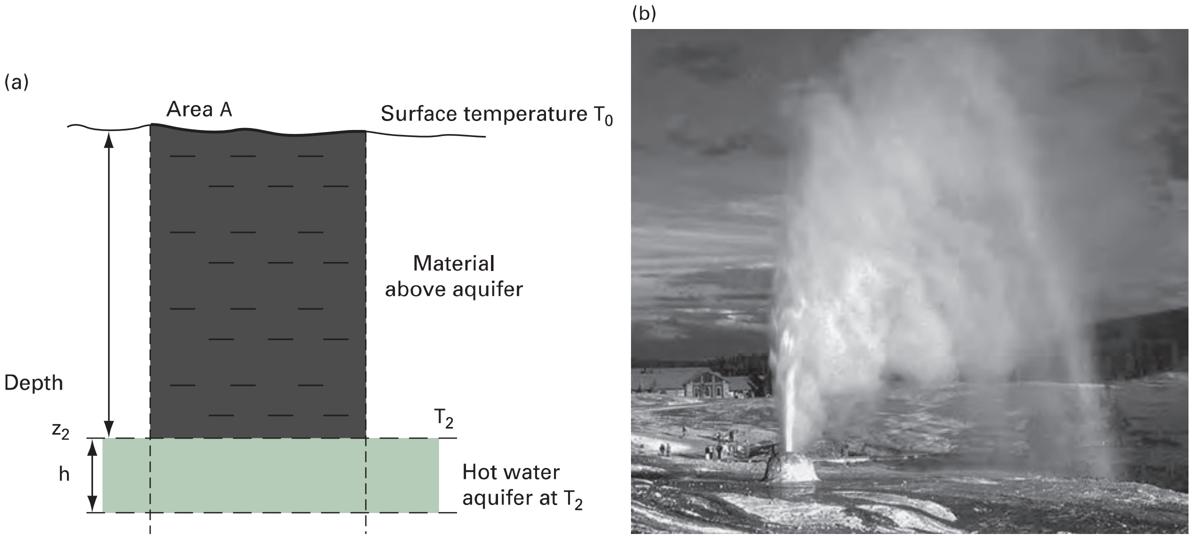


Fig. 14.5

a Profile of hot aquifer system for calculating the heat content;
b a geyser, a common sight in many hydrothermal regions.

WORKED EXAMPLE 14.1 (After Garnish (1976))

1. Calculate the useful heat content per square kilometre of dry rock granite to a depth of 7 km. The geothermal temperature gradient G is constant at 40°C/km. The minimum useful temperature for power generation is 140 K more than the surface temperature T_0. $\rho_r = 2700$ kg/m^3, $C_r = 820$ J kg^{-1} K^{-1}.
2. What is the time constant for useful heat extraction using a water flow rate of 1.0 m^{3}s^{-1}km^{-2}?
3. What is the useful heat extraction rate initially and after 10 years?

Solution

At depth 7 km the temperature T_2 is 7 km × 40 K/km = 280 K more than T_0. The minimum useful temperature is 140 K more than T_0, which occurs at depth 140/40 km = 3.5 km. Thus only rock between depths of 3.5 km and 7 km is usable.

So by (14.7),

1
$$\begin{aligned} E_0 / A &= \rho_r c_r G(z_2 - z_1)^2 / 2 \\ &= (2.7\times 10^3 \text{kg m}^{-3})(0.82\times 10^3 \text{J kg}^{-1}\text{K}^{-1})(40\text{K/km})(7.0\text{km} - 3.5\text{km})^2 /2 \\ &= (2.7\times 0.82\times 40\times 3.5\times 3.5)(10^6)\text{m}^{-3}\text{J.km}^{-1}.\text{km}^2/2 \\ &= (543\times 10^6 \ \text{J.km}^{-3})\times(10^9\text{km}) = 543\text{x}10^{15}\text{J/km}^2 \\ &= 5.4\times 10^{17}\text{J/km}^2 \end{aligned} \tag{14.16}$$

2 Substituting in (14.12):

$$\tau = \frac{\rho_r A c_r (z_2 - z_1)}{\dot{V}\rho_w c_w} = \frac{1}{(\dot{V}/A)} \times \frac{\rho_r}{\rho_w} \times \frac{c_r}{c_w} \times (z_2 - z_1)$$

$$= \left(\frac{1}{1\text{m}^3\text{s}^{-1}\ \text{km}^{-2}}\right)\left(\frac{2700}{1000}\right)\left(\frac{820}{4200}\right)(3.5\ \text{km}) \tag{14.17}$$

$$= 1.84 \times (\frac{\text{km}^3}{\text{m}^3\text{s}^{-1}}) = 1.84x10^9\,\text{s} = 58\text{y}$$

3 By (14.15),

$$\left(\frac{\text{d}E}{\text{d}t}\right)_{t=0} = \frac{5.4\times 10^{17}\,\text{J km}^{-2}}{1.84\times 10^9\,\text{s}} = 290\ \text{MW km}^{-2} \tag{14.18}$$

$$\left(\frac{\text{d}E}{\text{d}t}\right)_{t=20\text{y}} = 290\,\text{MW.km}^{-2}\exp(-10/58) = 250\text{MW km}^{-2} \tag{14.19}$$

§14.3.2 Hot aquifers: algebra to calculate potential rate of heat extraction

In a hot aquifer, the heat resource lies within a layer of water deep beneath the ground surface (Fig. 14.5(a)). We assume that the thickness of the aquifer (h) is much less than the depth (z_2) below ground level, and that consequently the water is all at temperature T_2. The porosity, p', is fraction of the aquifer containing water, assuming the remaining space to be rock of density ρ_r. The minimum useful temperature is T_1. The characteristics of the resource are calculated similarly to those for dry rock in §14.3.1.

$$T_2 = T_0 + \frac{\text{d}T}{\text{d}z} z = T_0 + Gz \tag{14.20}$$

$$\frac{E_0}{A} = C_a(T_2 - T_1) \tag{14.21}$$

where C_a is the effective thermal capacitance of the aquifer volume considered; compare:

$$C_a = [p'\rho_w c_w + (1-p')\rho_r c_r]Ah \tag{14.22}$$

As with (14.9) onward, we calculate the removal of heat by a water volume flow rate $\dot{V}$ at θ above T_1:

$$\dot{V}\rho_w c_w \theta = -C_a \frac{\text{d}\theta}{\text{d}t} \tag{14.23}$$

So

$$E = E_0 \exp(-t / \tau_a) \tag{14.24}$$

$$\frac{\mathrm{d}E}{\mathrm{d}t} = -(E_0/\tau_a)\exp(-t / \tau_a) \tag{14.25}$$

and

$$\tau_a = \frac{C_a}{\dot{V}\rho_w c_w} = \frac{[p'\rho_w c_w + (1-p')\rho_r c_r]h}{\dot{V}\rho_w c_w} \tag{14.26}$$

WORKED EXAMPLE 14.2 (After Garnish (1976))

1 Calculate the initial temperature, and heat content per square kilometre above 40°C, of an aquifer of thickness 0.5 km, depth 3 km, porosity 5%, under sediments of density 2700 kg/m^3, specific heat capacity 840 J kg^{-1} K^{-1}, temperature gradient 30°C/km. Suggest a use for the heat if the average surface temperature is 10°C.

2 What is the time constant for useful heat extraction with a pumped water extraction of 0.1 m^{3}s^{-1}km^{-2}?

3 What is the thermal power extracted initially and after 10 years?

Solution

1 Initial temperature:

$$T_2 = 10^\circ\mathrm{C} + (30\times 3)\mathrm{K} = 100^\circ\mathrm{C} \tag{14.27}$$

From (14.22),

$$\begin{aligned} C_a &= [(0.05)(1000)(4200) + (0.95)(2700)(840)](\mathrm{kg\ m^{-3}\,J\,kg^{-1}\,K^{-1}})(0.5\,\mathrm{km}) \\ &= 1.18\times 10^{15}\,\mathrm{J\ K^{-1}\ km^{-2}} \end{aligned} \tag{14.28}$$

With (14.21),

$$\begin{aligned} E_0 &= (1.18\times 10^{15}\,\mathrm{J\ K^{-1}\ km^{-2}})(100-40)^\circ\mathrm{C} \\ &= 0.71\times 10^{17}\,\mathrm{J\ km^{-2}} \end{aligned} \tag{14.29}$$

The quality of the energy (see §14.4.2) is suitable for factory processes or household district heating.

2 In (14.26),

$$\begin{aligned} \tau_a &= \frac{(1.2\times 10^{15}\,\mathrm{J\ K^{-1}km^{-2}})}{(0.1\,\mathrm{m^3\ s^{-1}\ km^{-2}})(1000\,\mathrm{kg\ m^{-3}})(4200\,\mathrm{J\ kg^{-1}K^{-1}})} \\ &= 2.8\times 10^9\ \mathrm{s} = 90\ \mathrm{y} \end{aligned} \tag{14.30}$$

3 From (14.25),

$$\begin{aligned} \left(\frac{\mathrm{d}E}{\mathrm{d}t}\right)_{t=0} &= \frac{(0.71\times 10^{17}\,\mathrm{J\ km^{-2}})}{(2.8\times 10^9\,\mathrm{s})} \\ &= 25\,\mathrm{MW\ km^{-2}} \end{aligned} \tag{14.31}$$

Check:

$$\begin{aligned} \left(\frac{\mathrm{d}E}{\mathrm{d}t}\right)_{t=0} &= \dot{V}\rho_w c_w (T_2 - T_1) \\ &= (0.1\,\mathrm{m^3s^{-1}km^{-2}})(1000\,\mathrm{kg\ m^{-3}})(4200\ \mathrm{J\ kg^{-1}K^{-1}})(60\ \mathrm{K}) \\ &= 25\,\mathrm{MW\ km^{-2}} \end{aligned}$$

From (14.25),

$$\left(\frac{\mathrm{d}E}{\mathrm{d}t}\right)_{t=10\mathrm{y}} = 25\,\mathrm{MWkm}^{-2}\exp(-10/90) = 22\,\mathrm{MW\,km}^{-2} \qquad (14.32)$$

§14.4 HARNESSING GEOTHERMAL RESOURCES

Geothermal power arises from heat sources having a great range of temperatures and local peculiarities. In general, available temperatures are much lower than from furnaces; therefore, although much energy is accessible, the thermodynamic quality is poor. The sources share many similarities with industrial waste heat processes and ocean thermal energy conversion (Chapter 13). In this section we will review the strategy for using geothermal energy.

§14.4.1 Matching supply and demand

The heat from geothermal sources tends to be available at significantly lower temperatures than heat from fuels; therefore the efficiency of electricity generation is less. Nevertheless, exporting energy via electricity networks is convenient and often meets national needs. If the waste heat from generation can be utilized, so much the better. Electricity generation will probably be attractive if the source temperature is >300°C, and unattractive if <150°C. Nevertheless, the energy demand for heat at <100°C is usually greater than that for electricity, and so the use of geothermal energy as heat is important, even when the geothermal resource is not 'good enough' for electricity generation (see §14.4.5).

Several factors fix the scale of geothermal energy use. The dominant costs are capital costs, especially for the boreholes, whose costs increase exponentially with depth. Since temperature increases with depth, and the value of the energy increases with temperature, most schemes settle on optimum borehole depths of ~5 km. Consequently, the scale of the energy supply output is usually ≥100 MW (electricity and heat for high temperatures, heat only for low temperatures), as shown in Examples 14.1 and 14.2.

The total amount of heat extractable from a geothermal source can be increased by re-injecting the partially cooled water from the above-ground heat exchanger back into the reservoir, but at significant cost. This has the extra advantage of disposing of the effluent, which may have about 25 kg/m^3 of solute and be a substantial pollutant (e.g. unfit for irrigation) (see §14.6).

§14.4.2 Extraction techniques: hydrothermal

The most successful geothermal projects have boreholes sunk into natural water channels in hyperthermal regions (Fig. 14.6). This is the method used at Wairakei, New Zealand (Fig. 14.10), and at the geysers in California. Similar methods are used for extraction from hot aquifers in semithermal regions, where natural convection can be established from the borehole without extra pumping.

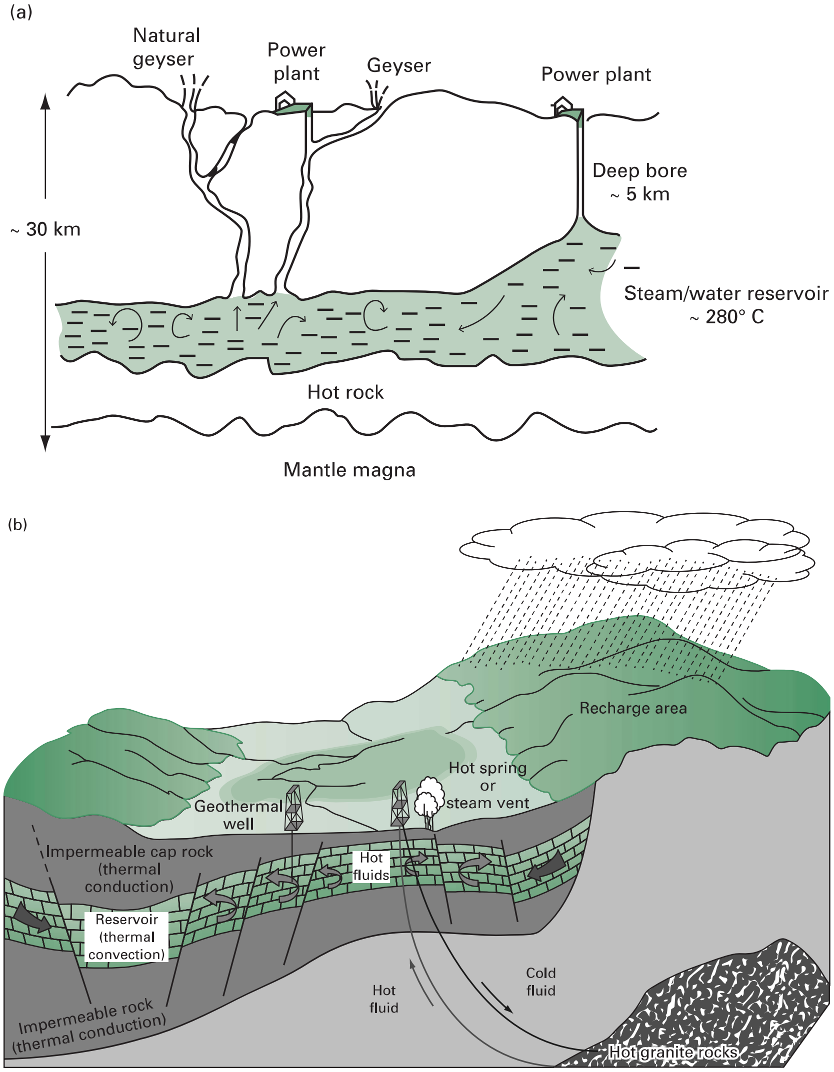


Fig. 14.6

a Schematic diagram, not to scale, of hydrothermal power stations in a hyperthermal region (e.g. the Geysers geothermal field, California).

b Geology of an aquifer in a hydrothermal region (left of diagram) and a region of hot, dry rock (right of diagram) (not to scale). The diagram also indicates some of the flows of heat ('broad' arrows) and water ('line' arrows) relevant to geothermal power.

§14.4.3 Extraction techniques: 'enhanced geothermal systems' (EGS)

Sources of 'hot, dry rock' (HDR) are much more abundant than hydrothermal regions: temperatures of 200°C are accessible under a significant proportion of the world's landmass. This has motivated expensive research and development in the USA and Europe on techniques to harness this heat for electricity power generation. One result has been the recognition that few basement rocks are completely dry, but there are many regions where utilization of their geothermal heat requires 'enhanced geothermal systems', in which re-injection is necessary to maintain commercial production.

In the 1980s, the research group at the Los Alamos Scientific Laboratory, USA pioneered methods of fracturing the rock with pressurized cold water around the end of the injection borehole (Fig. 14.7). After initial fracturing, water was pumped down the injection bore to percolate upwards through the hot rock at depths of ~5 km and temperatures ~250°C before returning through shallower return pipes. Using such 'enhanced geothermal systems' (EGS), complex arrays of injection and return boreholes might, in principle, enable gigawatt supplies of heat to be obtained. However, it has proved difficult to constrain the fracturing so that a large enough fraction of the injected water emerges from the outflow pipes; the injected water leaks into other fractures and is lost, as indicated in Fig. 14.7.

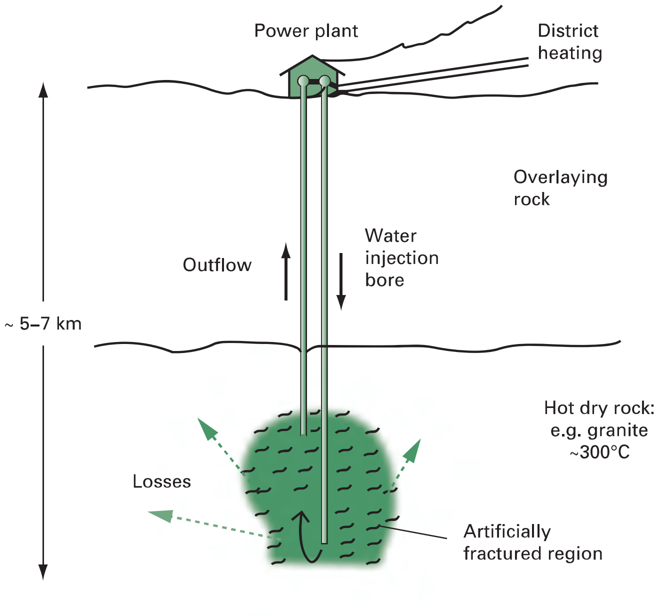


Fig. 14.7

Schematic diagram of heat extraction from a hot, dry rock system. Black arrows indicate the desired direction of water flow; green (dashed) arrows indicate water lost by 'undesired' paths through the fractured zone.

These technical difficulties and large costs of EGS have limited development to only a few pilot plants, mainly in Europe and the USA. Nevertheless, the 1.7 MW_e 'Desert Peak 2' system in Nevada, USA operated commercially in 2013. For EGS to become a worldwide application with reasonable power output, the technology will have to be scaled up in stages from pilot plants of ~1 MW_e to the range of 50 to 200 MW_e. To achieve this by 2025, as envisaged by the IEA Geothermal Roadmap, will require strong policy and funding support.

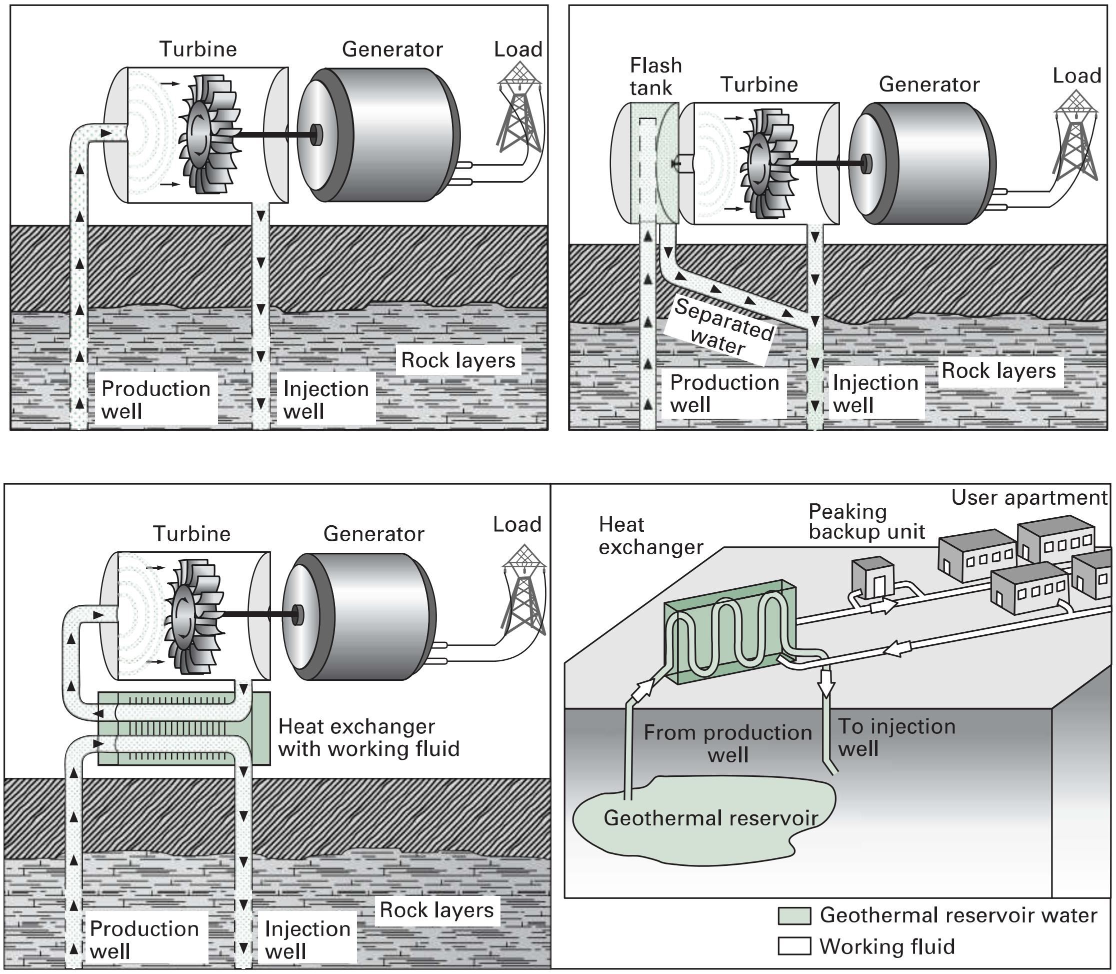
§14.4.4 Electricity-generating systems

The choice of the heat exchange and turbine system for a particular geothermal source is complex, requiring specialist experience. Fig. 14.8 sketches some of the system configurations in common use. Nearly always the emerging bore water after use is re-injected into the reservoir. The simplest systems pass 'dry' steam from the ground directly into a steam turbine (Fig. 14.8(a)), as used in the first-ever geothermal power plant in Italy in 1904, and subsequently in other places (e.g. Wairakei, New Zealand: Fig. 14.10). The geothermal reservoir contains superheated water at temperatures >180°C and at large pressure. As the water flows to the surface, the pressure decreases and some boils ('flashes') into steam, which is injected into steam turbines that power the generators (Fig. 14.8(b)). In other situations, water at lower temperatures (110°C to 180°C) heats other working fluids, usually organic compounds, in a heat exchanger; these generally boil at about 80°C, so providing the pressurized vapor to a turbine (Fig. 14.8(c)). The turbines operate with a Rankine cycle, as for OTEC and solar ponds (see Box 13.1). In the heat exchangers, the counter-flowing fluids are separate, yet nevertheless difficulties occur owing to deposits and corrosion from the chemicals in the cooling borehole water. Similar problems occur for ocean thermal energy conversion (Chapter 13).

§14.4.5 Direct uses of geothermal heat

Despite using insulated pipes, heat cannot be distributed effectively over distances greater than ~30 km, so use of geothermal must be near to the supply. In cold climates, household and business district-heating schemes have proved viable if the population density is ≥350 people/km^2 (>100 premises/km^2). Thus a 100 MW_{th} geothermal plant can serve an urban area ~20 km × 20 km at ~ 2 kW_{th} per premises. Other heating loads are for glasshouse heating, fish farming, food drying, factory processes, etc.

Table 14.2 lists some of the main direct uses of geothermal heat and the countries having the largest use. Only Iceland and Japan are



(a) Dry-steam power plant

(b) Flashed-steam power plant

(c) Binary cycle power plant

(d) District heating system

Fig. 14.8

Schematic diagrams of applications of geothermal heat:
a to **c** three types of electricity generating system,
d district heating system. For more details, see text.

Source: After EERE (2004).

also major producers of geothermal electricity (Table 14.1); moreover, in Iceland, geothermal energy is the principal source for both electricity and heating. Because direct heating applications (unlike electricity) can use geothermal sources at temperatures <100°C, many more countries use geothermal sources for heat than for electricity. Table 14.1 also indicates that many of the countries with the highest quality geothermal sources are in the Tropics, and so have little need for space heating.

Table 14.2 Direct applications of geothermal heat, 2010.

Application	*Installed capacity* GW_{th}	*No. of countries reporting*	*Largest users by nation [a]*	*Average capacity factor Z*	*Remarks*
Space heating	5.4	24	Iceland, China, France, Turkey, Russia	0.47	Mainly district heating
Bathing and swimming	6.7	67	China, Japan, Turkey, Brazil, Mexico	0.52	Estimates [b]
Greenhouse heating	1.5	34	Turkey, Hungary, Russia, China, Italy	0.48	
Aquaculture	0.6	22	China, USA, Italy, Iceland, Israel	0.56	
Crop drying	0.1	14		0.42	
Industrial uses	0.5	14	Iceland	0.70	
Other uses	0.4				
Subtotal (excl GHP)	**15.3**				
Geothermal (near-surface) heat pumps	35.2	43	USA, China, Switzerland, Norway, Germany	0.19	In USA, mostly for cooling in summer

Notes

a Iceland is the largest user *per capita* in every category except GHP.

b In many geothermally heated baths/pools, hot water flows continuously whether the pool is in use or not.

Source: Data from the survey by Lund *et al.* (2010).

§14.5 GROUND-SOURCE HEAT PUMPS (GHP)

Heat pumps driven by a power source provide heating and/or cooling, and are often described as a form of renewable energy (§14.1). Heat passes into a built space (heating) or out of the space (cooling), either (i) having been extracted from the ground or outside air (heating); or (ii) passing into the ground or air (cooling). When most of the energy exchange is with local ground or water, the technology is called '*Ground-source heat pumps* (GHP)'. The systems exchange heat with the nearly constant temperature, T_g, beneath ground at depths from 2 to 50 m, providing heat in winter and cooling in summer. T_g at 2 m depth commonly equals the annual average temperature above ground (see Problem 14.3 to appreciate why T_g remains nearly constant at this value). Although this energy exchange is not related to the deep geophysical phenomena outlined in §14.2, we include the technology in this same chapter because of its popular, yet inaccurate, description as a 'geothermal heat pump', which implies that it is a form of geothermal energy. When the exchange is with the air, it is called '*Air-source heat pump*'.

A heat pump is essentially a 'refrigerator working backwards'. A motor, usually electric, operating at power P_m enables the device to extract heat at a rate P_g from the air or ground of the outside environment, and deliver heat flow P_{out} for a purpose. Setting $P_{out} = C_{cop}P_m$ defines the coefficient of performance (COP); here with the symbol C_{cop}. Thermodynamic analysis treats a heat pump as a thermal engine in reverse (Fig. 14.9(b)). In heating mode heat P_g is taken from the ground using motor of power P_m; so heat $P_{out} = P_g + P_m$ is delivered. In heating mode, the COP is $P_{out}/P_m = 1 + (P_g/P_m)$; in cooling mode the COP is in effect P_g/P_m.

For a commercial ground-sourced heat pump, C_{cop} is about 3 to 5, depending on the temperatures at input and output. So the user receives 3 to 5 more heat with a heat pump than by dissipating the electric power directly as heat. (For an air-source heat pump, C_{cop}, is generally less at about 2.) The temporarily cooled environment is restored by renewable energy entering from the wider environment. All 'air conditioners' are heat pumps, and many can switch between heating 'as a heat pump' or cooling 'as a refrigerator'.

For a closed loop 'ground-sourced heat pump' (GSHP), P_g is obtained from a transfer fluid (perhaps water) circulating inside the pipes of a buried heat exchanger. This may be constructed as long pipes arranged horizontally under, typically, a garden or car park, or as vertical pipes in relatively deep boreholes (Fig. 14.9(a)). For the latter, the structural foundation piles of commercial-scale buildings can be used in dual purpose. A typical installation may extract $(P_g) \approx 50$ kWh/(m^2 year) from the ground around the heat exchanger for perhaps 25% of the time (~2000 h/y) in winter to heat a thermostatically heated space. This allows the original temperature of the ground around the heat exchanger to be restored

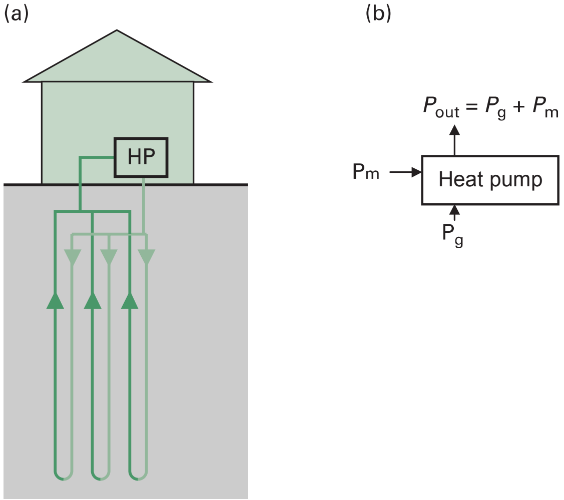


Fig. 14.9

'Geothermal' heat pumps:

a schematic diagram of one popular configuration, with closed loop of working fluid in the near-surface ground;

b energy flows described in text.

by thermal conduction through the soil and, possibly, by groundwater movement. The source of most of this restored heat is usually from sunshine and ambient air above the ground, rather than from any significant thermal flow upwards from geothermal sources; the average geothermal flux is <0.4 W/m², which is insignificant. In practice, for heating an insulated building, the area needed for the capture of the heat through horizontal heat exchangers is about 1.5 times the outside wall area of the building.

When operating for cooling, the heat pump reverses flow to act as a refrigerator, so adding heat to the underground surroundings. For deep, vertically orientated heat exchangers (e.g. if combined with structural piling), the underground surroundings heat in summer and cool in winter, so becoming a heat store with a six-month reversible cycle.

The capacity factors for GHPs are small compared to other direct uses of geothermal heat (Table 14.2) because GHPs are rarely used throughout the year, and are often oversized for peak summer and/or winter use.

The optimum theoretical performance is as a Carnot cycle operating between input absolute temperature T_g, and output temperature T_{out}, so:

$$C_{cop}^{(carnot)} = P_{out}/P_m = T_{out}/(T_{out} - T_g). \tag{14.33}$$

With $T_{out} = 298$ K (25°C) and $T_g = 278$ K (5°C), $C_{cop}^{(carnot)} = 15$. However, this 'ideal' is much larger than the values of 3 to 6 obtained in practice for ground-sourced heat pumps, since the Carnot analysis assumes infinitely slow, reversible processes.

§14.6 SOCIAL AND ENVIRONMENTAL ASPECTS

Geothermal power from hydrothermal regions has a proven record of providing generally safe and reliable electrical power generation at relatively low cost. Consequently its use has increased steadily during the past few decades (see Fig. 14.1). Capital costs of new systems are about US$2500 per installed kilowatt (electric) capacity, which are similar to those of nuclear and hydro power stations. Power is generated continuously at full rating, with reductions for maintenance and repair, so average capacity factors are ~70% (Table 14.1) and similar to coal and nuclear plant, i.e. annual output is ~70% of full rating for 8760 hours per year. Thus, in favorable sites, the levelized cost of electricity production is competitive with conventional (brown) sources, being especially so if external costs are included (see Table D.4 in Appendix D). Once utilized, the heat-extracting fluids are either discharged at surface level or re-injected. Surface discharge requires careful environmental monitoring and may be ecologically damaging. Re-injection of pressurized fluids into the reservoir generally improves the energy extraction, but may cause micro-earthquakes if forced into deep formations. Hydrogen sulphide gas may be emitted with the fluids, being unpleasant to smell yet not generally at concentrations to be dangerous. Water quality monitoring in the vicinity is essential to monitor dissolved chemicals.

Resources of 'hot-dry-rock' (HDR) are much more abundant than hydrothermal resources: temperatures of 200°C are accessible under a large proportion of the world's landmass. Goldstein *et al.* (2011) indicate that if 'enhanced geothermal systems' (EGS) were to become successful at a commercial scale, then the electricity-generating capacity from geothermal sources could be comparable to global primary energy supply (i.e. >20 EJ/y). Unfortunately, even after several decades of technical development, EGS are still only at a 'pilot plant' stage.

For geothermal power, the size of the resource is unconfirmed until drilling takes place, as with oil or mining projects. After such prospecting, successful geothermal projects take at least five to seven years to develop from resource discovery to commercial development. Long development times and the upfront financial risk of the cost of exploration make development of the resource particularly difficult in developing countries with visible geothermal activity at a plate boundary but limited power demand, such as the Solomon Islands, the smaller islands of Indonesia or parts of East Africa.

Ground-source heat pumps are a totally different technology from geothermal energy extraction. They are usually for small-scale supply of building space heat and hot water, and may be reversed for cooling. They are a mature and reliable technology, with millions of units operating worldwide.

We illustrate the environmental impacts of geothermal power through the example of the 140 MW_e Wairakei power station in New Zealand (Fig. 14.10). The station was built in the 1950s in one of the most geologically active areas in the world. The wells (top left of the photo) tap into a mixture of water and steam; the hot water is separated with the high-pressure steam being directed through the pipes to the power station at bottom right. At Wairakei there is a considerable overpressure in the boreholes. The clouds of steam at top left come from the hot water boiling as the pressure on it is released.

Removal of the hot water from the ground through the power station resulted in subsidence affecting some local buildings. Consequently, some of the output water flow was re-injected into the area, alleviating the difficulty. There has been a diminution in the intensity of some of the natural geysers of the area due to power stations, although most remain substantially unaffected. Note that such a negative impact on natural geothermal phenomena inhibits the wider use of geothermal power in Japan.

At the bottom of the photograph of Fig.14.10 is the Waikato River, which both provides cooling water and receives the condensed steam and other emissions at discharge. The inherent emission of H_2S is treated before discharge. The Waikato is one of the largest rivers in the country,

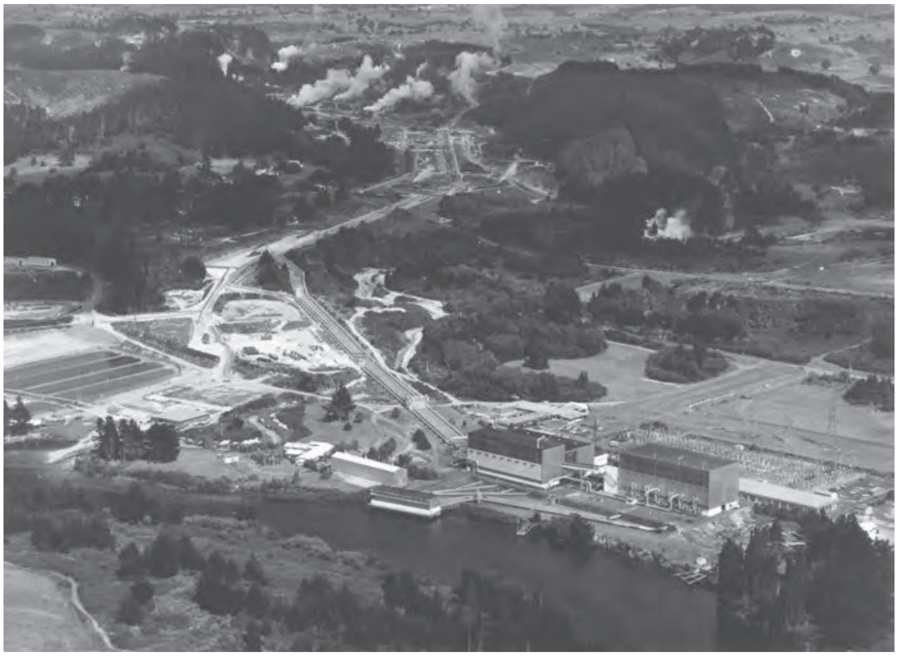


Fig. 14.10

The Wairakei geothermal power station in New Zealand. Well-heads are at the top of the photo; condensed steam is discharged into the Waikato River at the bottom.

so the discharged heat and remaining chemicals are rapidly diluted. An environmental study in 2001 found that downstream concentrations of the chemical elements As, B and Hg, and of dissolved ammonia, were all much less than the permitted limits for water with native fish.

Geothermal systems also emit the greenhouse gas CO_2. Wairakei's emission of 0.03 $kgCO_2$ /kW_eh is less than the average concentration for geothermal power station emission of ~0.1 kg CO_2/ kW_eh produced, which is much less than the typical value of 1.0 kg CO_2/ kW_eh from a coal-fired power station. The benefit/cost ratio of geothermal systems is improved by making use of the low-grade heat leaving the power station. At Wairakei, a prawn farm benefits from this; it is visible at the rectangular areas at the left of the photograph.

CHAPTER SUMMARY

There are two main uses of geothermal energy, i.e. heat coming from the hot core of the Earth, accessed from depths from 1 to 5 km.

1 At a few locations, geothermal heat is available at temperatures >150°C, coupled with a natural flow of high-pressure water/steam, so enabling *electrical power* generation from turbines. Several important geothermal electric power complexes are fully established, especially in Italy, Iceland, New Zealand and the USA. The worldwide number of geothermal electrical power plants at such 'hydrothermal'