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Chapter 2

Solar thermal energy

By Bob Everett

2.1 Introduction

As we saw in Chapter 1, the Sun is the ultimate source of most of our renewable energy supplies. Since there is a long history of the Sun being regarded as a deity, the direct use of solar radiation has a deep appeal to engineer and architect alike.

In this chapter, we look at some of the methods employed to gather solar thermal or heat energy. Solar photovoltaic (PV) energy, the direct conversion of the Sun's rays to electricity, is dealt with in Chapter 3. Solar thermal collection methods are many and varied, so we can only give the briefest introduction and supply points to further reading for those interested in studying the subject in greater depth.

What sorts of system can be used to collect solar thermal energy?

Most systems for low-temperature solar heating depend on the use of glazing, in particular its ability to transmit visible light but block infrared radiation. High-temperature solar collection is more likely to employ mirrors to concentrate the Sun's radiation. In practice, solar energy systems of both types can take a wide range of forms. These include:

Active solar heating. This always involves a discrete **solar collector**, usually mounted on the roof of a building, to gather solar radiation. Mostly, collectors are quite simple and the heat will be at low temperature (under 100 °C) and used for domestic hot water or swimming pool heating.

Passive solar heating. This term has two slightly different meanings.

- In the 'narrow' sense, it means the absorption of solar energy directly into a building to reduce the energy required for heating the habitable spaces (i.e. what is called **space heating**). Passive solar heating systems mostly use air to circulate the collected energy, usually without pumps or fans – indeed the 'collector' is often an integral part of the building.
- In the 'broad' sense, it means the whole process of integrated low-energy building design, effectively to reduce the heat demand to the point where small passive solar and other 'free heat' gains make a significant contribution in winter. A large solar contribution to a large heat load may look impressive, but what really counts is to minimize the total fossil fuel consumption and thus achieve the minimum cost. This is a key feature of *superinsulated* or *Passivhaus* building design.

Daylighting. This means making the best use of natural daylight, through both careful building design and the use of controls to switch off artificial lighting when there is sufficient natural light available.

Solar thermal engines. These are an extension of active solar heating, usually using more complex collectors to produce temperatures high enough to drive steam turbines to produce electric power. They can come in a number of different types, but most of the world's solar thermally generated electricity is produced in California in multi-megawatt plants using large parabolic mirrors.

This chapter also briefly describes *heat pumps*. These draw heat energy from the outside environment which, in the 2009 EU Renewable Energy Directive (CEC, 2009), is classified as renewable energy. The heat gains from air-source heat pumps may sometimes be categorized as 'solar energy' although they do not *directly* depend on the availability of solar radiation. The gains from ground-source heat pumps are categorized in the EU Directive as 'geothermal energy', a topic described further in Chapter 9.

It must be stressed at the outset that making the best use of solar energy requires a careful understanding of the climate of any particular location. Indeed, many of our present energy problems stem from attempts to produce buildings inappropriate to the local climate. This can mean that the economics of solar technologies commonly used in southern Europe may be disappointing when transferred, for example, to northern Scotland.

However, most of the methods described in this chapter have been well tried and tested over the past century. Even the most spectacular of modern solar thermal-electric power stations are just uprated versions of inventive systems built at the beginning of the 20th century. The skill of using solar thermal energy, in all its forms, perhaps lies in producing systems that are cheap enough to compete with 'conventional' systems based on fossil fuels at current prices.

2.2 The rooftop solar water heater

For most people, 'solar heating' means the rooftop solar water heater. In Europe by 2010 there were almost 35 million square metres of solar collectors installed, 13 million m^2 in Germany but only about 570 000 m^2 in the UK (ESTIF, 2011). Most use simple flat plate collectors. There are two basic forms of system: pumped or thermosyphon.

The pumped solar water heater

This is the form most common in northern Europe, normally roof-mounted (Figure 2.1). A typical flat plate pumped system consists of three elements as shown in Figure 2.2.

.1 Solar panels on roof (photo of Arcon)

(1) A collector panel, typically of 3–5 square metres in area, tilted to face the Sun and mounted on the normal pitched roof of a house, as in Figure 2.1. This panel itself normally consists of three components (see Figure 2.3). The main absorber might be a steel plate bonded to copper or steel tubing through which water circulates. The plate is sprayed with a special black paint or coated with a selective surface to maximize the solar absorption. It is normally covered with a single sheet of glass or plastic and the whole assembly is insulated on the back to cut heat losses.

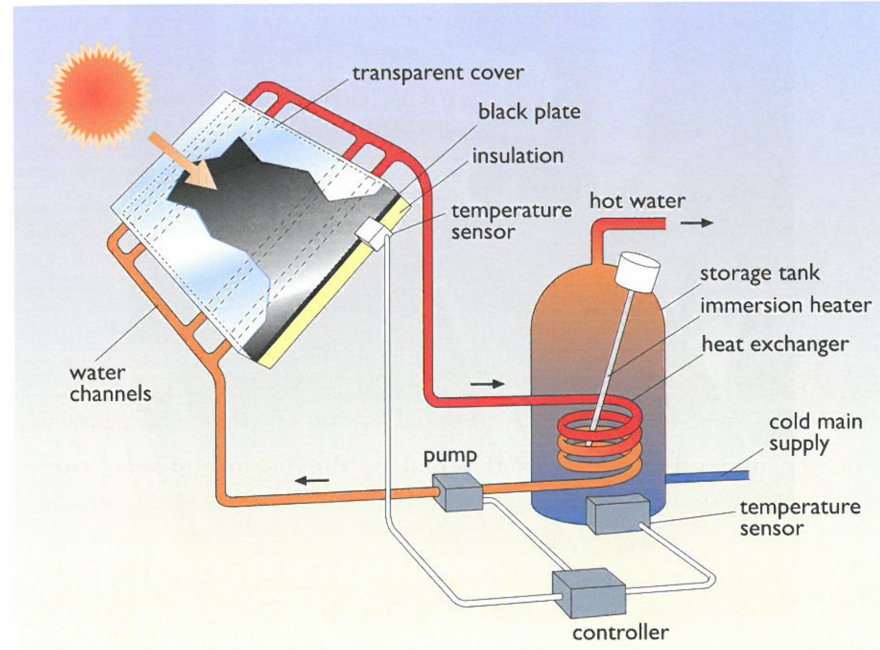


Figure 2.2 Pumped active solar water heater

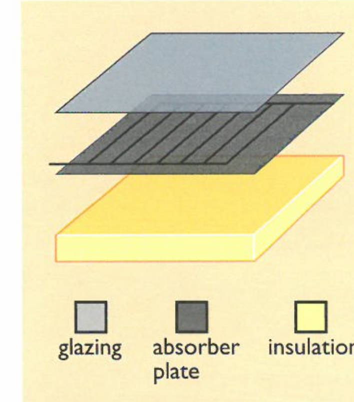


Figure 2.3 Components of a solar panel

(2) A storage tank, typically of around 200 litres capacity, which often doubles as the normal domestic hot water cylinder. This usually contains an electric immersion heater for winter use. The tank is insulated all round, typically with 50 mm of glass fibre or polyurethane foam. The hot water from the panel circulates through a heat exchanger at the bottom of the tank.

(3) A pumped circulation system to transfer the heat from the panel to the store. Sensors detect when the collector is becoming hot and switch on an electric circulating pump. Since in northern Europe the collector has to be able to survive freezing temperatures, the circulating water contains an antifreeze. Non-toxic propylene glycol is often used (instead of the poisonous ethylene glycol commonly used in car engines).

In the UK, field trial results suggest that such a system can typically provide over 1100 kWh y^{-1} or about 40% of a household's hot water (EST, 2011a).

The thermosyphon solar water heater

In frost-free climates where it is safe to mount the storage tank outdoors, a simpler **thermosyphon** arrangement can be used, as shown in Figure 2.4.

This design dispenses with the circulation pump. It relies on the natural convection of hot water rising from the collector panel to carry heat up to the storage tank, which must be installed above the collector. There is no need for a heat exchanger as the required domestic hot water circulates directly through the panel.

Normally the storage tank also contains an electric immersion heater for top-up and use on cloudy days. Mediterranean systems are usually designed

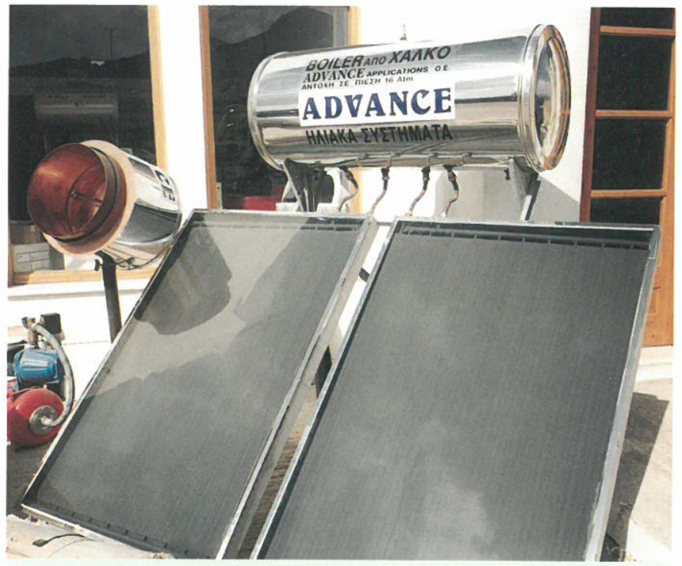


Figure 2.4 A typical Mediterranean thermosyphon solar water heater – the insulated storage tank is at the top

to be free-standing for mounting on buildings with flat roofs. Given the higher levels of solar radiation in these countries, they are usually sold with only around 2 m^2 of collector area.

2.3 The nature and availability of solar radiation

The wavelengths of solar radiation

The Sun is an enormous nuclear fusion reactor, which converts hydrogen into helium at the rate of 4 million tonnes per second. It radiates energy by virtue of its high surface temperature, approximately 6000 °C. Of this radiation, approximately one-third of that incident on Earth is simply reflected back. The rest is absorbed and eventually retransmitted to deep space as long-wave infrared radiation. On average the Earth re-radiates just as much energy as it receives and sits in a stable energy balance at a temperature suitable for life.

We perceive solar radiation as white light. In fact it spreads over a wide spectrum of wavelengths, from 'short-wave' infrared (longer than red light) to ultraviolet (shorter than violet). The pattern of wavelength distribution is critically determined by the temperature of the surface of the Sun (see Figure 2.5).

The Earth, which has an average atmospheric temperature of –20 °C and a surface temperature of 15 °C, radiates energy as long-wave infrared to deep space, the temperature of which is only a few degrees above the absolute zero value, –273 °C. We tend to forget this outgoing radiation, but its effects can be observed on a clear night when a ground frost can occur as heat radiates first to the cold upper atmosphere and then out into space.

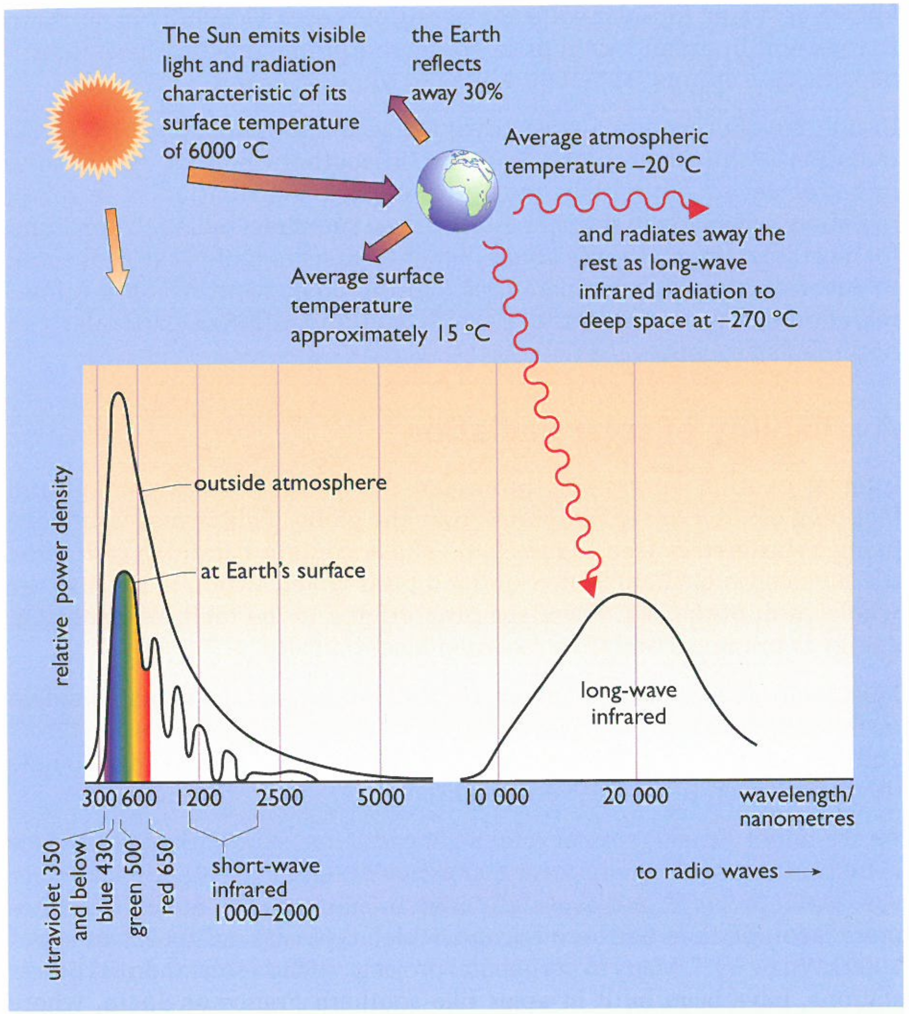


Figure 2.5 Radiation of energy to and from the Earth

As we shall see, most of the art of low-temperature solar energy collection depends on our ability to use glass and surfaces with selective properties that allow solar radiation to pass through but block the re-radiation of long-wave infrared. The gathering of solar energy for high-temperature applications, such as driving steam engines, mainly involves concentrating solar energy using complex mirrors.

Direct and diffuse radiation

When the Sun's rays hit the atmosphere, more or less of the light is scattered, depending on the cloud cover. A proportion of this scattered light comes to Earth as **diffuse radiation**. On the ground this appears to come from all over the sky. Some of it we see as the blue colour of a clear sky, but most is the 'white' light scattered from clouds.

What we normally call 'sunshine', that portion of light that appears to come straight from the Sun, is known as **direct radiation**. On a clear day, this can approach a power density of 1 kilowatt per square metre (1 kW m^{-2}), known as '1 sun' for solar collector testing purposes. Generally in northern Europe and in urban locations in southern Europe, practical peak power densities are around 900–1000 watts per square metre.

In northern Europe, on average over the year approximately 50% of the radiation is diffuse and 50% is direct. In southern Europe, where solar radiation levels are higher, most of the extra contribution is in direct radiation, especially in summer. Both diffuse and direct radiation are useful for most solar thermal applications, but only direct radiation can be focused to generate very high temperatures. On the other hand it is the diffuse radiation that provides most of the 'daylight' in buildings, particularly in north-facing rooms.

2.6 A solarimeter (also as a pyranometer)

Availability of solar radiation

Interest in solar energy has prompted the accurate measurement and mapping of solar energy resources over the globe. This is normally done using **solarimeters** (see Figure 2.6). These contain carefully calibrated thermoelectric elements fitted under a glass cover, which is open to the whole vault of the sky. A voltage proportional to the total incident light energy is produced and then recorded electronically.

Most solarimeter measurements are recorded simply as **total energy incident on the horizontal surface**. More detailed measurements separate the direct and diffuse radiation. These can be mathematically recombined to calculate the radiation on tilted and vertical surfaces.

As we might expect, annual total solar radiation on a horizontal surface is highest near the equator, over 2000 kilowatt-hours per square metre per year (kWh m^{-2} y^{-1}), and especially high in sunny desert areas. These are more favoured than northern Europe, which typically only receives about 1000 kWh m^{-2} y^{-1}. Many experimental projects, such as solar thermal power stations, have been built in areas like southern France or Spain, where radiation levels are around 1500 kWh m^{-2} y^{-1}, or the southern USA, where levels can reach 2500 kWh m^{-2} y^{-1}.

It is obvious that in Europe summers are sunnier than winters, but what does that mean in energy terms?

On average in July, the solar radiation on a horizontal surface in northern Europe (e.g. Ireland, UK, Denmark and northern Germany) is between 4.5 and 5 kWh m^{-2} per day (see Figure 2.7). Five kilowatt-hours represents about half of the daily average energy consumption for water heating for an average UK household. At 2009 UK domestic fuel prices, this amount of heat would cost approximately 25p if it was obtained from a high-efficiency gas boiler, or slightly more using off-peak electricity. In southern Europe (Spain, Italy and Greece), July solar radiation levels are higher, between 6 and 7.5 kWh m^{-2} per day.

In winter, however, the amount of solar radiation is far lower. In January on average in northern Europe it can be only one-tenth of its July value, around 0.5 kWh m^{-2} per day (see Figure 2.8), yet in southern Europe there may still be appreciable amounts, 1.5 to 2 kWh m^{-2} per day.

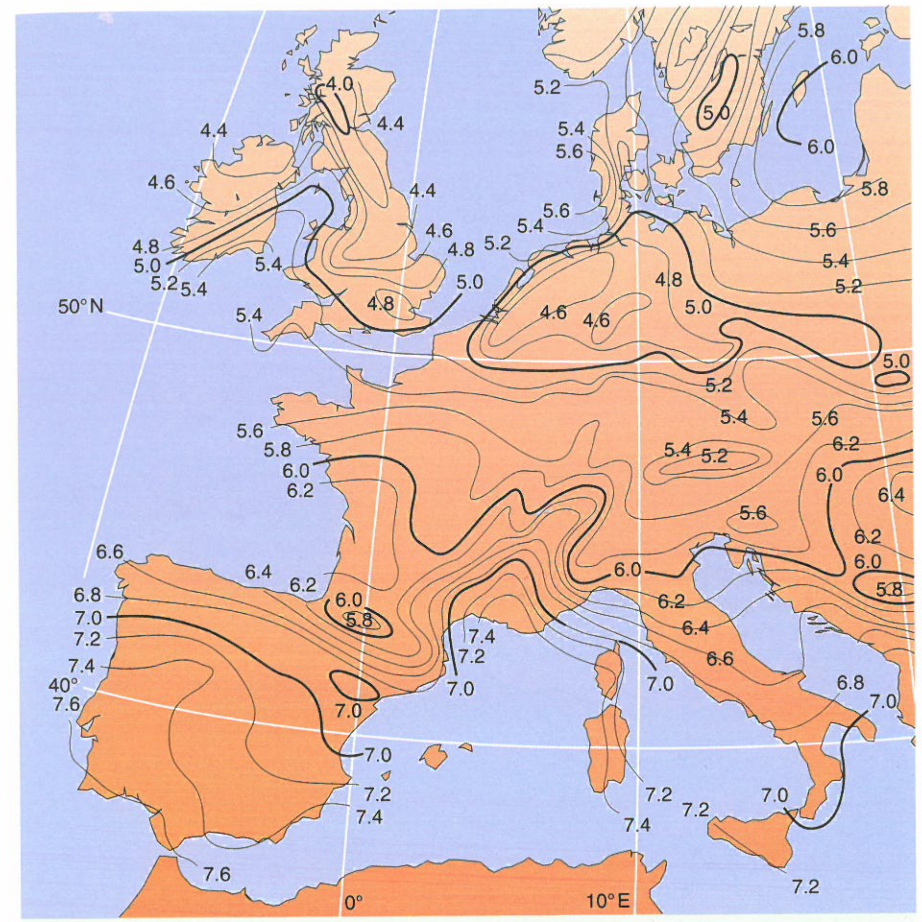


Figure 2.7 Solar radiation on horizontal surface (kWh per square metre per day), Europe, July (source: CEC, 1994)

The implications of this are that in northern Europe we need to look for applications that require energy mainly in the summer. In southern Europe, there may be enough radiation in the winter to consider year-round applications.

Tilt and orientation

So far, we have talked about solar radiation on the horizontal surface. To collect as much radiation as possible, a surface should face south (assuming it is in the northern hemisphere) and must be tilted towards the Sun. How much it should be tilted is dependent on the latitude and at what time of year most solar collection is required.

If the tilt angle between a surface and the horizontal is equal to the latitude, it will be perpendicular to the Sun's rays at midday in March and September (see Figure 2.9).

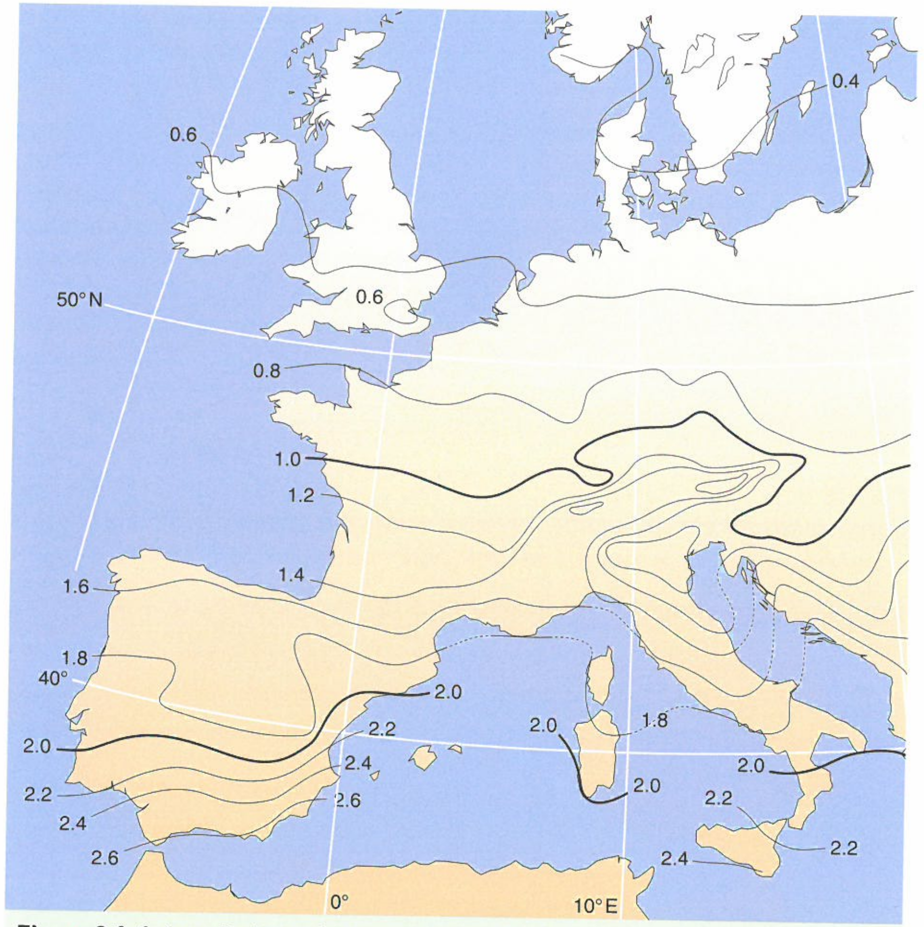


Figure 2.8 Solar radiation on horizontal surface (kWh per square metre per day), Europe, January (source: CEC, 1994)

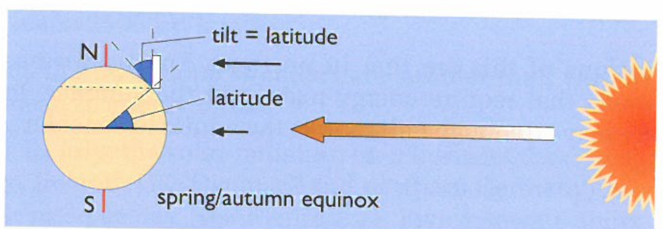


Figure 2.9 A surface tilted at the latitude angle will be perpendicular to the Sun's rays at mid-day on the spring or autumn equinox

There is also the difference between summer and winter to consider. Box 2.1 explains why countries at high latitudes (such as the UK) receive more solar energy in summer than winter.

To maximize solar collection in summer (when there is most radiation to be had), the tilt angle should be less than the latitude. To maximize solar collection in winter (when more solar radiation may be needed) the tilt angle should be greater than the latitude angle (see Figure 2.12).

BOX 2.1 Solar radiation and the seasons

If the energy output of the Sun is constant, why does the UK receive more radiation in summer than in winter?

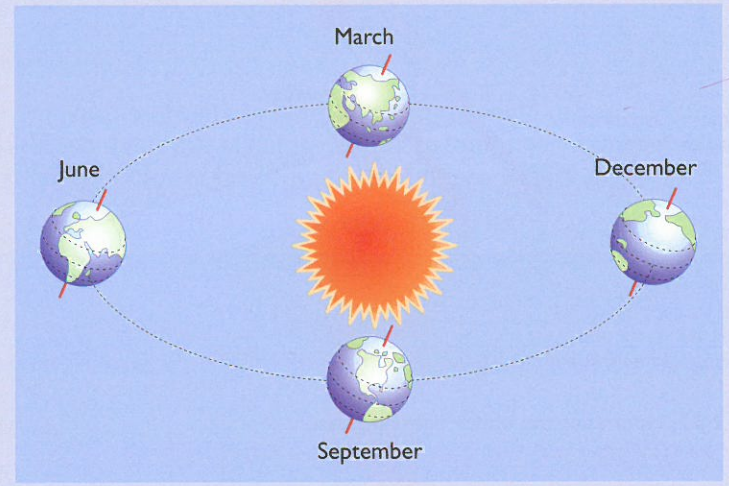


Figure 2.10 The Earth revolves around the Sun with its axis tilted at an angle of 23.5° to the plane of rotation

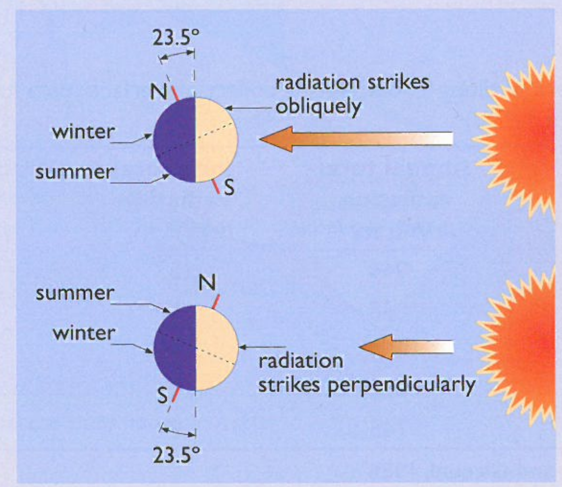


Figure 2.11 The tilt of the Earth's axis creates summer and winter

The Earth circles the Sun with its polar axis tilted towards the plane of rotation (Figure 2.10). In June, the North Pole is tilted towards the Sun. The Sun's rays thus strike the northern hemisphere more perpendicularly and the Sun appears higher in the sky (Figure 2.11). In December the North Pole is tilted away from the Sun and its rays strike more obliquely, giving a lower energy density on the ground (i.e. fewer kilowatt-hours reach each square metre of ground per day).

Another important factor is that the lower the Sun in the sky, the further its rays have to pass through the atmosphere, giving them more opportunity to be scattered back into space. When the Sun is at 60° to the vertical its peak energy density will have fallen to one-quarter of that when it is vertically overhead. This topic will be revisited in Chapter 3.

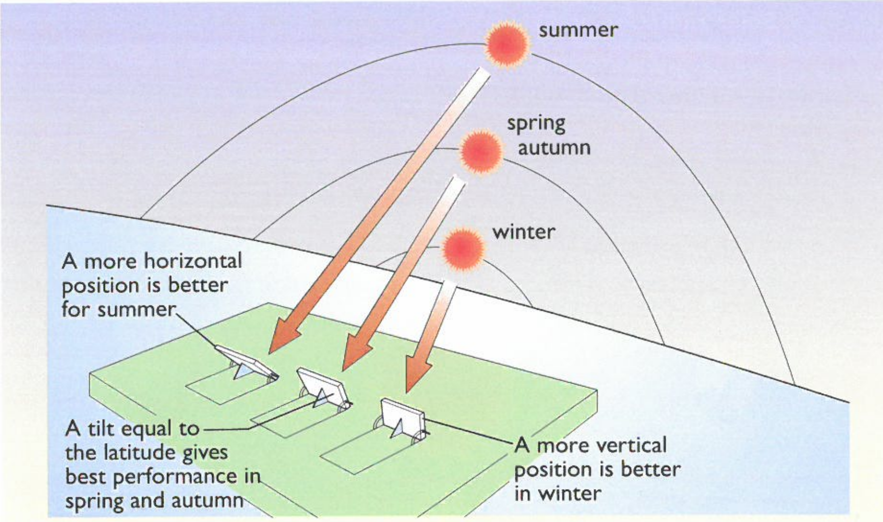


Figure 2.12 Optimizing the tilt for different seasons

Fortunately the effects of tilt and orientation are not particularly critical. Table 2.1 gives totals of energy incident on various tilted surfaces for Kew, near London.

Table 2.1 Effect of tilting a south-facing collection surface (data for Kew, near London, latitude 52° N)

Tilt /°	Annual total radiation /kWh m^{-2}	June total radiation /kWh m^{-2}	December total radiation /kWh m^{-2}
0 – Horizontal	944	153	16
30	1068	153	25
45	1053	143	29
60	990	126	30
90 – Vertical	745	82	29

Source: Achard and Gicquel, 1986

Similarly, the effects of orientation away from south are relatively small. For most solar heating applications, collectors can be faced anywhere from south-east to south-west. This relative flexibility means that a large proportion of existing buildings have roof orientations suitable for solar energy systems. This conclusion applies to both solar thermal and solar photovoltaic (PV) systems.

2.4 The magic of glass

Most low-temperature solar collection is dependent on the properties of one rather curious substance – glass. It is hard to imagine a world without glazed windows. They have been around since the time of the Romans, who invented a process for making plate glass, although the ability to make large sheets of glass was lost in the aptly named 'Dark Ages' and did not reappear until the 17th century.

Transparency

Glass is transparent to visible light and short-wave infrared radiation but has the added advantage of being opaque to long-wave infrared re-radiated from a solar collector or building behind it (see Figure 2.13).

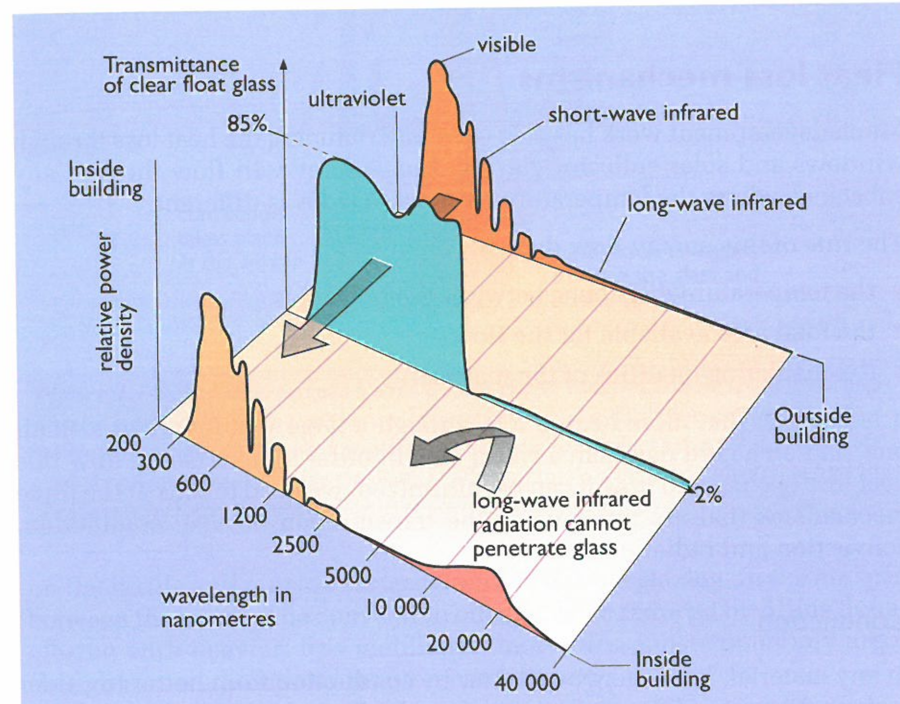


Figure 2.13 Spectral transmittance of glass

Over the past few decades, enormous effort has been put into improving the performance of glazing, both to increase its transparency to visible radiation, and to prevent heat escaping through it.

Manufacturers strive to make glass as transparent as possible, i.e. they try to maximize its **transmittance**, the fraction of incident light that passes through it. They usually do this by minimizing the iron content of the glass. Certain plastics that have optical properties similar to glass can be used instead, although normally they must be protected from the damaging effects of ultraviolet light.

Table 2.2 shows the optical properties of commonly used glazing materials. They share the property of a high solar transmittance (close to 1.0), but the long-wave infrared transmittance is very low by comparison.

Table 2.2 Optical properties of commonly used glazing materials

Material	Thickness /mm	Solar transmittance	Long-wave infrared transmittance
Float glass (normal window glass)	3.9	0.83	0.02
Low-iron glass	3.2	0.90	0.02
Perspex	3.1	0.82	0.02
Polyvinyl fluoride (tedlar)	0.1	0.92	0.22
Polyester (mylar)	0.1	0.87	0.18

Heat loss mechanisms

Much development work has also gone into reducing the heat loss through windows and solar collector glazing. Heat energy will flow through any substance where the temperature on the two sides is different.

The *rate* of this energy flow depends on:

- the temperature difference between the two sides
- the total area available for the flow
- the insulating qualities of the material.

It is obvious that more heat is lost through a large window than a small one, and on a cold day than a warm one. In order to understand how this heat loss occurs, and how it can be minimized, we need to look at the three mechanisms that are involved in the transmission of heat: conduction, convection and radiation.

Conduction

In any material, heat energy will flow by **conduction** from hotter to colder regions. The rate of flow will depend on the first two factors listed above, and on the **thermal conductivity** of the material.

Generally, *metals* have very high thermal conductivities and can transmit large amounts of heat for small temperature differences. Where the frames of glazing systems are made of metal, they should include an insulated thermal break to minimize heat loss.

Insulators require a large temperature differential to conduct only a small amount of heat. Still air is a very good insulator. Most practical forms of insulation rely on very small pockets of air, trapped for example between the panes of glazing, as bubbles in a plastic medium, or between the fibres of mineral wool.

Convection

A warmed fluid, such as air, will expand as it warms, becoming less dense and rising as a result, creating a fluid flow known as **convection**. This is one of the principal modes of heat transfer through windows and out to the environment (see Figure 2.14). It occurs between the air and the glass

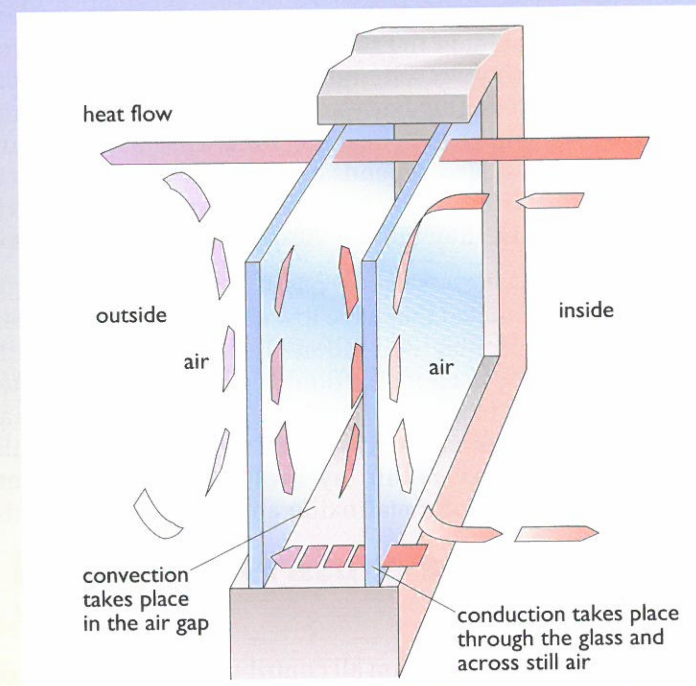


Figure 2.14 How heat escapes from a double-glazed window. The air space is normally about 16 mm wide. If it is too narrow, convection will be difficult but conduction will be easy because there is only a small thickness of air to conduct across. If it is too wide, convection currents can easily circulate. In addition there is infrared radiation across the air space which can be reduced by using low emissivity coatings

on the inside and outside surfaces, and, in double glazing, in the air space between the panes. The convection effects can be reduced by filling double glazing with heavier, less mobile gas molecules, most commonly argon, though carbon dioxide or krypton can be used.

Convection can also be reduced by limiting the space available for gas movement. This is the principle used in the insulation materials mentioned above.

Various forms of **transparent insulation** have been developed that use a transparent plastic medium containing bubbles of trapped insulating gas. These materials could eventually revolutionize the concept of windows (and walls), but at present the materials are expensive, not robust and need protection from the rigours of weather and ultraviolet light.

Alternatively double glazing can be evacuated. Convection currents cannot flow in a vacuum. However, a very high vacuum is required and it needs to last for the whole life of the window, 50 years or more. Also the window will need internal structural spacers to stop it collapsing inwards under the air pressure on the outside. These spacers conduct heat across the gap, slightly reducing the overall performance.

A simpler way to reduce the convection effects is to insert extra panes of glass or of transparent plastic film between the other two, turning double glazing into triple or quadruple glazing.

Radiation

Heat energy can be **radiated**, in the same manner as it is radiated from the Sun to the Earth. The quantity of radiation is dependent on the temperature difference between the radiating body and its surroundings. The roof of a building, for example, will radiate heat (i.e. long-wave infrared radiation) away to the atmosphere. It also depends on a quality of the surface known as **emissivity**. Most materials used in buildings have high emissivities of approximately 0.9, that is, they radiate 90% of the theoretical maximum for a given temperature.

Other surfaces can be produced that have low emissivities. This means that although they may be hot, they will radiate little heat outwards. **'Low-E' coatings** are now normally used inside double glazing to cut radiated heat losses from the inner pane to the outer one across the air gap. There are two basic types. 'Hard coat' uses a thin layer of tin oxide, giving an emissivity of about 0.15. 'Soft coat' uses very thin layers of optically transparent silver sandwiched between layers of metal oxide and gives a better emissivity of about 0.05.

Window *U*-value

Conduction, convection and radiation all contribute to the complex process of heat loss through a wall, window, roof, etc. In practice, the actual performance of any particular building element is usually specified by a ***U*-value**, defined so that:

heat flow rate per square metre = *U*-value × temperature difference.

The units in which *U*-values are expressed are thus watts per square metre per kelvin (W m^{-2} K^{-1}). As pointed out in Chapter 1 temperatures can be measured in degrees Celsius (°C) or kelvins (K). The size of a degree is the same on both scales, so temperature differences are identical in °C and K and *U*-values will often be seen written in units of W m^{-2} $°C^{-1}$.

The lower the *U*-value, the better the insulation performance. Table 2.3 gives typical *U*-values of various types of window glazing system (the precise values will depend on construction details, particularly the details of the frames). By way of comparison: 10 cm of opaque fibreglass insulation has a *U*-value of 0.35 W m^{-2} K^{-1}. Box 2.2 gives a sample energy calculation.

Table 2.3 Indicative *U*-values for windows with wood or PVC-U frames

Glazing type	W m^{-2} K^{-1}
Single glazing	4.8
Double glazing (normal glass, air filled)	2.7
Double glazing (hard coat low-e, emissivity = 0.15, air filled)	2.0
Double glazing (hard coat low-e, emissivity = 0.2, argon filled)	2.0
Double glazing (soft coat low-e, emissivity = 0.05, argon filled)	1.7
Triple glazing (soft coat low-e, emissivity = 0.05, argon filled)	1.3

Source: BRE, 2005

BOX 2.2 *U*-value and heat loss

What is the rate of heat loss through a large single-glazed window with an area of 2 m^2, on a day when the outdoor and indoor temperatures are 5 °C and 20 °C respectively?

Table 2.3 shows that the *U*-value for this window is 4.8 W m^{-2} K^{-1}, so the loss rate is

$$2 \times 4.8 \times (20 - 5) = 144 \text{ W}$$

Note that, if the temperature difference remained the same throughout 24 hours, the total loss would be almost 3.5 kWh. If this window was replaced with the best of the glazing types shown in Table 2.3, this loss would be reduced to under 1 kWh. Although windows are an important route by which solar energy can be collected, their role in cutting unnecessary heat losses is just as important.

2.5 Low-temperature solar energy applications

We have seen how solar radiation can produce low-temperature heat. Just how useful is this?

As we saw in Chapter 1, Figure 1.5, in the UK about a third of all the end-use of fuel is for low-temperature space and water heating. About 80% of delivered energy use in the domestic sector is in this form (see Figure 2.15).

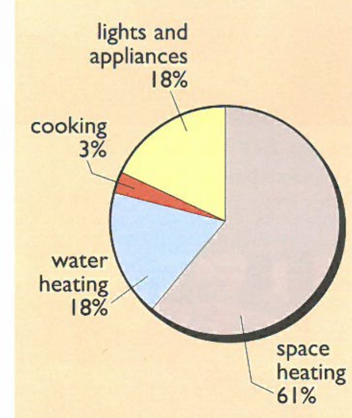


Figure 2.15 Breakdown of UK domestic sector energy use 2009 (DECC, 2011a)

Although simple solar systems are in principle ideal for supplying this heat, there are other potential competitors. These include:

- district heating fed by waste heat from existing conventional power stations or from industrial processes
- small-scale combined heat and power generation plant
- heat pumps (see Box 2.3).

All of these merit further development, and unlike solar heating, most have the advantage of being able to run all year round.

Swimming pools are another potential application. They do not use a significant proportion of Europe's total energy consumption, since there are not very many of them, but individually they can be enormous energy users. A large, indoor leisure pool in northern Europe can use 1 kW of power for every square metre of pool area continuously throughout the year. This kind of establishment is a prime candidate for the technologies listed above.

Outdoor pools, usually unheated, are rather different. Here the aim is to make the water a little more attractive when people come to use them, which is usually on sunny, warm days. This is ideal solar heating territory.

.3 Heat pumps

pump is essentially very similar to a refrigerator, except that in the UK it is likely to be primarily used for ; rather than cooling. Figure 2.16 shows the key elements of the most common type.

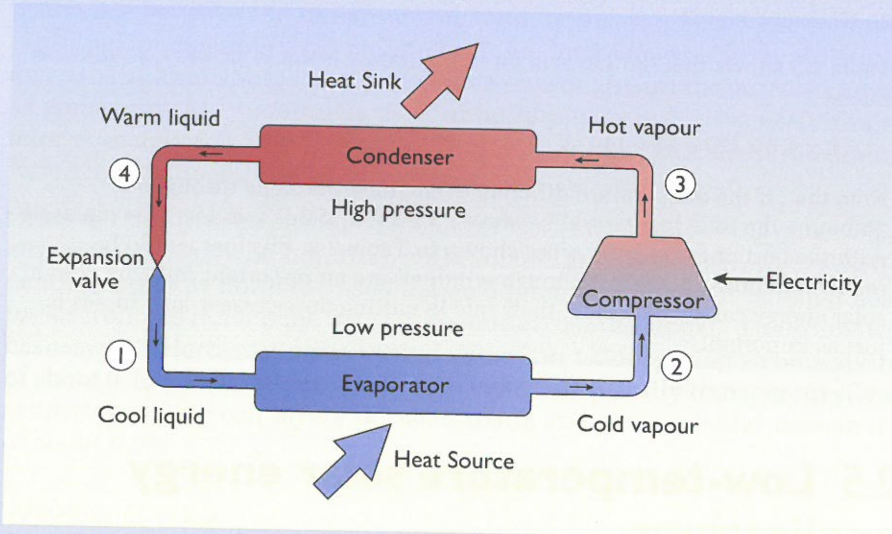


Figure 2.16 Schematic diagram of a heat pump (source: EST, 2010)

17 Fan-coil unit for an heat pump

3 Evaporator pipes laid or a ground-source heat

The heat pumping process is made possible by the use of a special **refrigerant** liquid that boils at low temperature (typically about −15 °C at atmospheric pressure, higher at higher pressures). At point (1) in Figure 2.16 this starts as a cool liquid at a low pressure. In order to convert a liquid to a vapour, it must be given energy – the so-called **latent heat of evaporation**. The refrigerant absorbs heat in a heat exchanger called the **evaporator** and vaporizes (point (2)). The vapour then enters an electrically driven compressor that raises both its pressure and temperature (point (3)). The hot vapour then enters another heat exchanger, the **condenser** where it condenses to a warm liquid and gives up its latent heat of evaporation (point (4)). Finally it is forced through a fine **expansion valve** or throttle where it loses pressure, vaporizing and dropping in temperature. It then repeats the cycle.

Overall, heat is 'pumped' from a low temperature in the evaporator to a higher temperature in the condenser. In a domestic refrigerator, the heat is absorbed in an evaporator inside the refrigerated compartment, thus lowering its temperature, and pumped to a condenser on the back of the refrigerator, where the heat is released, warming one's kitchen in the process.

In buildings a heat pump may be used for heating or cooling (more commonly known as air conditioning). When used for heating the evaporator is located somewhere in the external environment. An **air-source heat pump** is likely to have a *fan coil unit* such as that shown in Figure 2.17. A **ground-source heat pump** uses pipes buried in the soil. These may be laid in a shallow trench, as in Figure 2.18 or in a deep vertical borehole which may be 10 metres or more deep. Such systems are described in Chapter 9.

Heat is then pumped from the outside environment to a condenser inside the building, normally connected to a central heating system. The temperature of the heat is sufficient to be useful for heating purposes. Energy (usually electrical) is, of course, required to operate the compressor. The ratio of the heat output to the electrical input is known as the **coefficient of performance** (COP). For systems installed in the UK this typically has values of 2–3 (EST, 2010). In order to function in mid-winter, the evaporator has to be able to absorb heat from the external environment even though the external temperature may be very low (down to −5 °C in the UK). This requirement potentially limits the performance of air-source heat pumps. Burying the evaporator coil in the ground (or in a lake or river) provides a more stable temperature environment in extreme winter conditions and can result in higher COPs.

In an air-source heat pump, the heat that is drawn from the external environment is taken immediately from the outside air, cooling it in the process. In a ground-source heat pump, the same process takes place, but by cooling the ground (by only a degree or two) so that heat flows down into it from the air over a large area and a long time period.

Under the 2009 EU Renewable Energy Directive (CEC, 2009) heat *gains* from heat pumps, i.e. the difference between the heat output and the electricity input, are classified as renewable energy. Those from air-source heat pumps are termed *aerothermal*; those from rivers or lakes are *hydrothermal* and those from 'energy stored in the form of heat beneath the surface of solid earth' are classified as *geothermal*.

This system of classifications may be a source of confusion. Heat gains from heat pumps are beginning to feature in national renewable energy statistics and they may be classified together with solar gains although they do not *directly* depend on solar radiation for their performance. Ground-source heat pumps, particularly those using vertical borehole heat exchangers as described in Chapter 9, are likely to be classified as 'geothermal heat pumps'.

Domestic water heating

Domestic water heating is perhaps the best overall potential application for active solar heating in Europe. It is a demand that continues all year round and still needs to be satisfied in the summer when there is plenty of sunshine. In the UK in 2009 it accounted for approximately 5% of the total national delivered energy use. A typical UK household uses approximately 13 kWh per day of delivered energy for this purpose (DECC, 2011a). In practice, much of this can be simply lost as waste heat. Uninsulated hot water cylinders and unlagged pipework are common causes of such losses and even solar water heaters can suffer from this failing.

Incoming mains water is usually at a temperature close to that of the ground at about 1 metre depth, approximately 12 °C in the UK, varying only slightly over the year, and it has to be heated up to 60 °C. In many books it is suggested that temperatures as low as 45 °C are adequate, but recent concerns over Legionnaires' Disease, caused by *Legionella pneumophila* bacteria multiplying in warm water, have highlighted the need for a higher temperature.

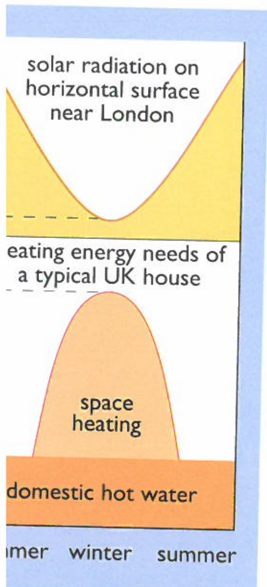
Domestic water heating is usually done in one of three ways:

- By electricity, with an immersion heater in a hot-water storage cylinder.
- Again using a storage cylinder, but with a heat exchanger coil inside connected to a central heating boiler (usually gas-fired) or possibly to a district heating supply system.
- By an 'instantaneous' heater, usually powered by gas or electricity.

In the UK, natural gas is the dominant fuel for domestic heating. As will be described later in Section 2.10, obtaining heat by burning natural gas directly involves less CO_2 production than using electricity generated from fossil fuels. Where solar heat can usefully substitute for heat produced by burning natural gas, every kilowatt-hour will save on the emission of about 0.2 kg CO_2. Where it substitutes for UK-generated electricity the figure is about 0.5 kg CO_2.

However, in many sunnier countries the majority of homes may use electric water heating throughout the year. In countries such as Greece, the electricity generation mix has a higher proportion of coal use than the UK and the emission savings may be closer to 0.7 kg CO_2 per kWh of heat produced (IEA, 2011). Also, in such countries, the national electricity demand is likely to peak in the summer, with ever-increasing demands for refrigeration and air-conditioning, rather than in the winter as in the UK. Thus every solar water heater installed saves not only on fuel, but, equally importantly, on building new power plants. Put another way, where solar heat can be substituted for fossil-fuelled electricity used for low-temperature heating purposes, this can be considered as beneficial as building a PV or solar thermal-electric power plant to generate an equivalent amount of extra electricity.

Domestic space heating



.19 The availability of
ation is out of phase
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Space heating involves warming the interior spaces of buildings to internal temperatures of approximately 20 °C. In the UK, it consumes almost 20% of the country's delivered energy, yet with an appropriate heating system it can in principle be carried out with water at only 45 °C. It is an activity that only occurs over the **heating season**. For normal UK buildings, this extends from about mid-September to April, although, as we shall see later in the section on passive solar heating, this can vary considerably with location and level of insulation.

However, there is a fundamental problem that for this application in the UK, as in much of northern Europe, the availability of solar radiation is completely out of phase with the overall demand for heat (see Figure 2.19). Although the total amount of solar radiation over a whole year on a particular site may far exceed the total building heating needs, the amount available during the heating season may be quite small.

Even with south-facing vertical surfaces, the amount of radiation intercepted in the UK over the winter is relatively small. In London, for example, over a typical six-month winter period of October to March, 1 m² of south-facing vertical surface will only intercept 250 kWh of solar radiation.

It is important to emphasize that the suitability of solar energy for space heating is dependent on the local climate. Textbooks may show quite grandiose solar buildings, but these may only be appropriate in particular locations, often places that are both cold and sunny in winter.

In summer, the UK has similar temperatures, and receives a similar amount of solar radiation, to other European countries on the same latitude.

In winter, the picture is different. The UK has relatively mild winters. However, the winter solar radiation remains largely dependent on latitude alone. As can be seen in Figure 2.20, average January temperatures in London are virtually identical to those in the south of France (follow the 5 °C contour).

Why then do northern Europeans go south for the winter? Because it is sunnier. As we saw from Figure 2.8, the south of France receives three times as much solar radiation on the horizontal surface in mid-winter as does London.

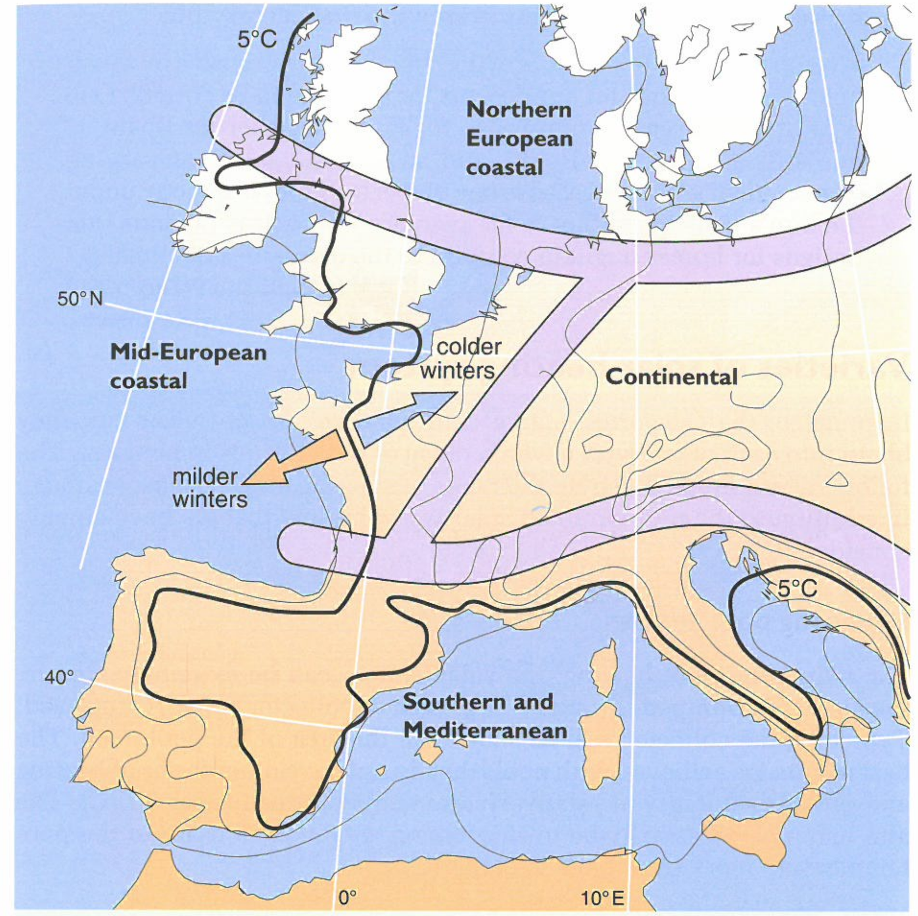


Figure 2.20 The different climatic zones of Europe. UK winters are mild compared with much of the rest of Europe. The 5 °C contour is for average January temperatures.

Broadly speaking, the climate of western Europe can be split into four regions (Figure 2.20):

(1) Northern European coastal zone: cold winters with little solar radiation in mid-winter; mild summers.

(2) Mid-European coastal zone: cool winters with modest amounts of solar radiation; mild summers.

(3) Continental zone: very cold winters with modest amounts of solar radiation; hot summers.

(4) Southern and Mediterranean zone: mild winters with high solar radiation; hot sunny summers.

It is no coincidence that many solar experimental projects have been built on the boundaries of regions 3 and 4, in the Pyrenees and the area around the Alps. This kind of climate is also typical of Colorado in the central USA, another area where solar-heated houses abound.

The broad view of passive solar heating is really about the subtle influence of climate on building design. Without this appreciation, it is all too easy to design buildings that are inappropriate to their surroundings.

As the Roman architect Vitruvius said in the first century BC:

> We must begin by taking note of the countries and climates in which homes are to be built if our designs for them are to be correct. One type of house seems appropriate for Egypt, another for Spain ... one still different for Rome, and so on with lands of varying characteristics. This is because one part of the Earth is directly under the Sun's course, another is far away from it ... It is obvious that designs for homes ought to conform to the diversities of climate.
>
> (Cited in Butti and Perlin, 1980)

Varieties of solar heating system

In practice, the categories 'active' and 'passive' are not clear cut: they blend into each other, with a whole range of possibilities in between. The following examples illustrate the range of solar heating systems available in addition to the roof-mounted solar water heaters that we have already considered.

Swimming pool heating

For swimming pool heating, the solar system can be extremely simple. Pool water is pumped through a large area of collector, usually unglazed. Typically, the collector will be about half the area of the pool itself. The best results are achieved with pools that do not have other forms of heating and are consequently at relatively low temperatures (under 20 °C). The aim may not necessarily be to save energy as much as to make the pool temperature more acceptable to bathers.

Conservatory (or 'sunspace')

A conservatory or greenhouse on the south side of a building can be thought of as a kind of habitable solar collector (see Figure 2.21(a)). Air is the heat transfer fluid, carrying energy into the building behind. The energy store is the building itself, especially the wall at the back of the conservatory.

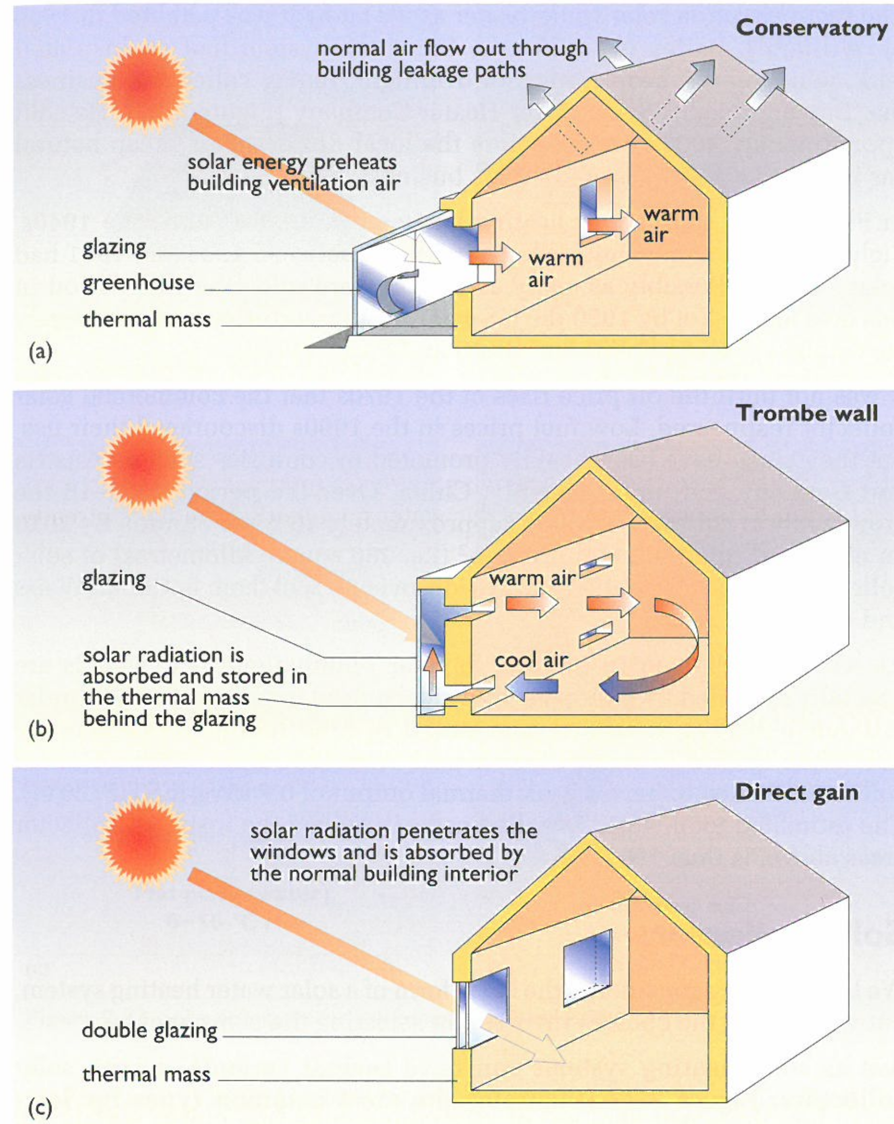
Trombe wall

With a Trombe wall (named after its French inventor, Félix Trombe), the conservatory is replaced by a thin air space in front of a storage wall (see Figure 2.21(b)). This is a solar collector with the storage immediately behind. Solar radiation warms the store and is radiated into the house in an even fashion from its inner side. In addition, on sunny days, air is circulated through the air space into the house behind. At night and on cold days, the air flow is cut off.

This concept can take many forms. Small collector panels can be built directly on to the existing walls of buildings. In the extreme, the air path can be omitted, and walls simply covered with 'transparent insulation'.

Direct gain

Direct gain is the simplest and most common of all passive solar heating systems (see Figure 2.21(c)). All glazed buildings make use of this to some degree. The Sun's rays simply penetrate the windows and are absorbed



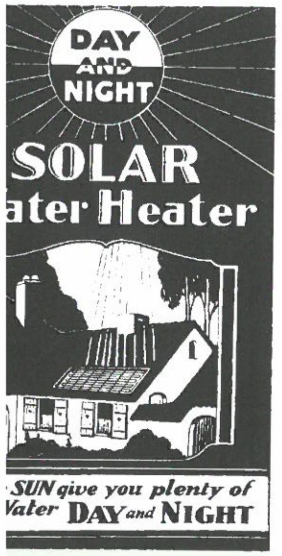
Figures 2.21 Different types of passive solar heating system: (a) conservatory; (b) Trombe wall; (c) direct gain

into the interior. If the building is 'thermally massive' enough, i.e. built of heavy materials such as concrete, and the heating system responsive, the gains are likely to be useful. If the building is too 'thermally lightweight', such as one of timber frame construction, it may overheat on sunny days and the occupants will perceive the effect as a nuisance.

2.6 Active solar heating

History

A solar water heater could be made simply by placing a tank of water behind a normal window. Indeed, many of the first systems produced in the USA in the 1890s were little more than this.



2.22 An advertisement ey's thermosyphon solar eaters, circa 1915

The thermosyphon solar water heater as we know it was patented in 1909 by William J. Bailey in California. Since the system had an insulated tank, which could keep water hot overnight, Bailey called his business the 'Day and Night' Solar Water Heater Company (Figure 2.22). He sold approximately 4000 systems before the local discovery of cheap natural gas in the 1920s virtually closed his business.

In Florida, the solar water heating business flourished until the 1940s. Eighty per cent of new homes built in Miami between 1935 and 1941 had solar systems. Possibly as many as 60 000 were sold over this period in this area alone. Yet by 1950 the US solar heating industry had completely succumbed to cheap fossil fuel (Butti and Perlin, 1980).

It was not until the oil price rises of the 1970s that the commercial solar collector reappeared. Low fuel prices in the 1990s discouraged their use, but they since have been heavily promoted in countries such as Austria and Germany and, more recently, China. Over the period 2005–10 the growth rate of collector sales was approximately 16% per annum. By 2010 an estimated total of 280 million m^2 (i.e. 280 square kilometres) of solar collectors had been installed worldwide, over 60% of them in China (Weiss and Mauthner, 2011).

As will be explained in Chapter 3, solar photovoltaic (PV) panels are normally specified by their peak electrical output expressed in kW$_p$ under full sunshine. For statistical comparability solar thermal collectors are now often quoted in terms of their peak *thermal* output, where 1 m^2 of collector is taken to have a peak thermal output of 0.7 kW$_{th}$ (ESTIF, 2011). The estimated total world installed capacity, given the installed collector areas above, is thus 196 GW$_{th}$.

Solar collectors

We have already considered the basic form of a solar water heating system, but what about the choices involved in selecting the components?

Just as solar heating systems can have several variants, so can solar collectors. Figure 2.23 illustrates the most common types for low-temperature use.

Unglazed panels (Figure 2.23(a)) are most suitable for swimming pool heating, where it is only necessary for the water temperature to rise by a few degrees above ambient air temperature, so heat losses are relatively unimportant.

Flat plate air collectors (Figure 2.23(b)) are not so common as water collectors and are mainly used for applications such as crop drying.

Glazed flat plate water collectors (Figure 2.23(c)) are, outside of China, the mainstay of domestic solar water heating. Usually they are only single glazed but may have an additional second glazing layer, sometimes of plastic. The more elaborate the glazing system, the higher the temperature difference that can be sustained between the absorber and the external air.

The absorber plate usually has a very black surface that absorbs nearly all of the incident solar radiation, i.e. it has a high **absorptivity**. Most normal black paints still reflect approximately 10% of the incident radiation (a white surface, by way of comparison, might reflect back 70–80%). Some panels use a **selective surface** that has both high absorptivity in

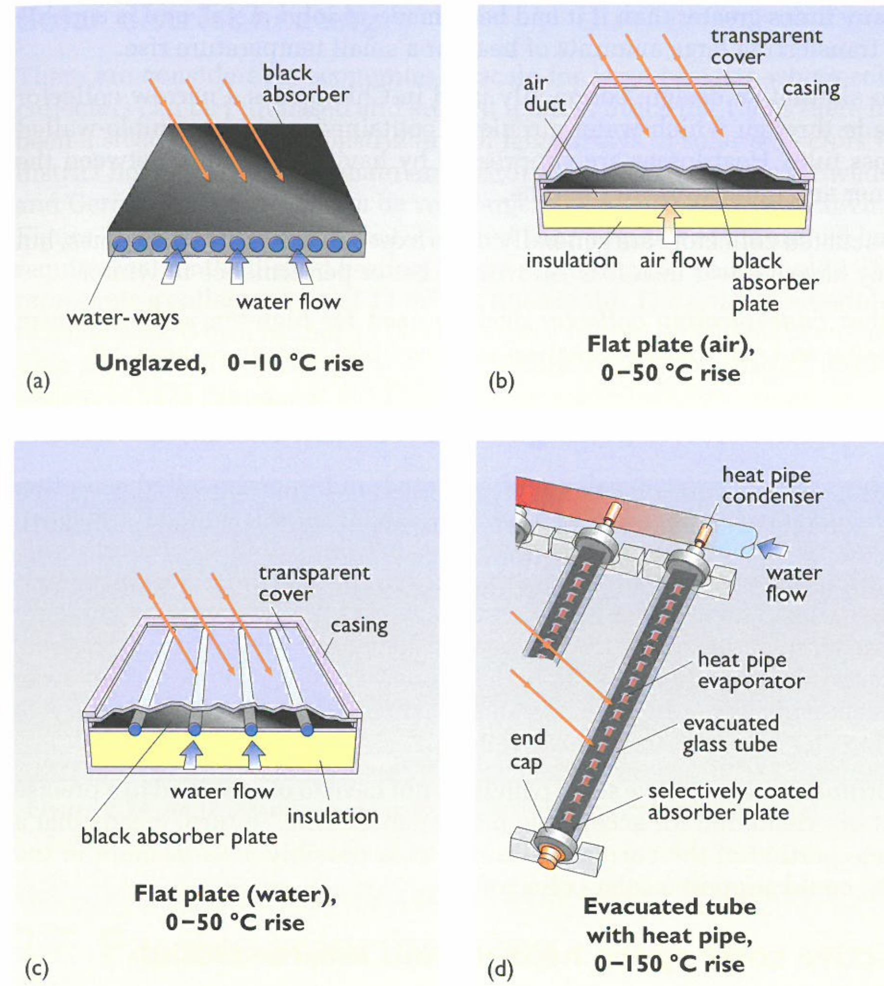


Figure 2.23 Solar collectors for low-temperature collection

the visible region and a low emissivity in the long-wave infrared to cut heat losses.

Many designs of absorber plate have been tried with success, including specially made pressed aluminium panels and small-bore copper pipes soldered to thick copper or steel sheet. Generally, an absorber plate must have high thermal conductivity, to transfer the collected energy to the water with minimum temperature loss.

Evacuated tube collectors. The example shown in Figure 2.23(d) takes the form of a set of modular tubes superficially similar to fluorescent lamps. The absorber plate is a metal strip down the centre of each tube. Convective heat losses are suppressed by a vacuum in the tube. The absorber plate uses a special 'heat pipe' to carry the collected energy to the water, which circulates along a header pipe at the top of the array. A **heat pipe** is a device that takes advantage of the thermal properties of a boiling fluid to carry large amounts of heat. A hollow tube is filled with a liquid at a pressure chosen so that it can be made to boil at the 'hot' end, but the vapour will condense at the 'cold' end. The tube in effect has a thermal conductivity many times greater than if it had been made of solid metal, and is capable of transferring large amounts of heat for a small temperature rise.

An alternative design, commonly used in China, uses a narrow collector blade through which water circulates contained within a double-walled glass tube. Heat losses are suppressed by having a vacuum between the inner and outer walls of the tube.

Evacuated collectors are generally more expensive than flat plate ones, but they have a lower heat loss, allowing a better performance in winter.

Other *concentrating collector* designs used for high-temperature steam raising and electricity generation are described later, in Section 2.9.

Robustness, mounting and orientation

Solar collectors are usually roof-mounted and once installed are often difficult to reach for maintenance and repairs. They must be firmly attached to the roof in a leak-proof manner and then must withstand everything that nature can throw at them – frost, wind, acid rain, sea spray and hailstones. They also have to be proof against internal corrosion and very large temperature swings. A double-glazed collector is potentially capable of producing boiling water in high summer if the heat is not carried away fast enough. It is quite an achievement to make something that can survive up to 20 or more years of this treatment.

Fortunately, as we have seen, panels do not have to be installed to a precise tilt or orientation for acceptable performance. This, in turn, means that a large portion of the current building stock, possibly 50% or more in the UK, could support a solar collector.

Active solar space heating and interseasonal storage

So far, we have looked in detail at domestic solar water heaters with only a few square metres of collector. It might be tempting to think that if a larger collector together with a much larger storage tank were fitted, solar energy could supply the annual low-temperature space heating needs of a building. However, as pointed out earlier, solar radiation is least available in mid-winter when it would be most needed for space heating.

One possibility is to increase the size of the storage tank so that summer sun could be saved right through to the winter. This is known as **interseasonal storage**. However, the difficulties of this should not be underestimated. The volume of hot water storage needed to supply the heating needs of a house may be almost the same size as the house itself. Also such a storage tank might need insulation half a metre thick to retain most of its heat from summer to winter. In order to reduce the ratio of surface area to volume, and hence heat loss, it pays to make the storage tank very large. This essentially limits the technology to large buildings or communal schemes.

Although experimental active solar space heating systems have been built, in practice it has generally proved simpler and more economical to save a kilowatt-hour of space heating energy through better insulation than to *supply* an extra one from active solar heating.

Solar district heating

There are considerable economies of scale for large projects where solar collectors can be purchased and erected in bulk. Since the 1980s there has been a steady stream of construction of large arrays of solar collectors for district heating systems in mainland Europe, mainly in Denmark, Sweden and Germany. The arrays can be very large. The 18 000 m^2 array shown in Figure 2.24 has a 12 100 m^3 heat store and supplies 30% of the annual heat requirement for the district heating system supplying 1600 households. This represents a collector area of 11 m^2 per household. The array is scheduled to be increased by a further 15 000 m^2 with a further 75 000 m^3 of storage. This should increase the share of heat production for the district heating system to 55% (Sunmark, 2011).

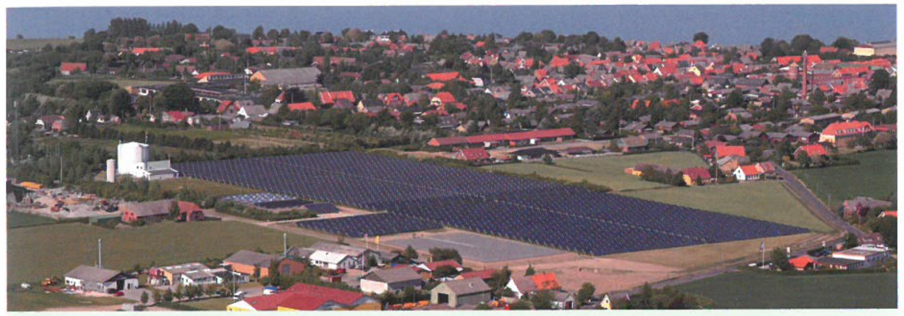


Figure 2.24 An 18 000 m^2 array of collectors feeding a district heating system at Marstal in Denmark

2.7 Passive solar heating

History

All glazed buildings are already to some extent passively solar heated – effectively they are live-in solar collectors. The art of making the best use of this dates back to the Romans, who put glass to good use in their favourite communal meeting place, the bath house. Window openings 2 m wide and 3 m high have been found at Pompeii.

After the fall of the Roman Empire, the ability to make really large sheets of glass vanished for over a millennium. It was not until the end of the 17th century that the plate glass process reappeared in France, allowing sheets of 2 m^2 or more to be made.

Even so, cities of the 18th and 19th centuries were overcrowded and the houses ill-lit. It was not until the late 19th century that pioneering urban planners set out to design better conditions. They became obsessed with the medical benefits of sunlight after it was discovered that ultraviolet light killed bacteria. Sunshine and fresh air became the watchwords of 'new towns' in the UK like Port Sunlight near Liverpool, built to accommodate the workers of a soap factory.

The planners then did not realize that ultraviolet light does not penetrate windows, but the tradition of allowing access for plenty of sunlight continues, reinforced by findings that exposure to bright light in winter is essential to maintain human hormone balances. Without it, people are likely to develop mid-winter depression.

Given the UK's past plentiful supply of coal, there was little interest in using solar energy to cut fuel bills. The construction of the Wallasey School building in Cheshire in 1961, inspired by earlier US and French buildings, was thus something of a novelty (see Figures 2.25 and 2.26).

Figure 2.25 Wallasey School, Cheshire, UK – built in 1961

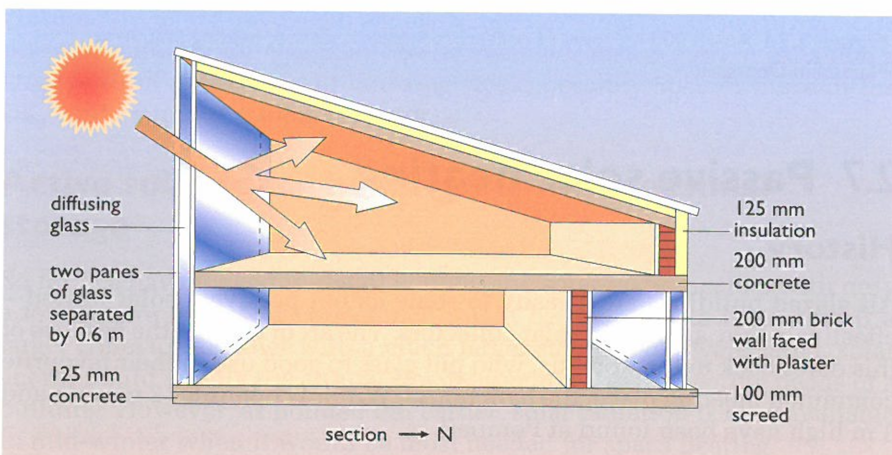


Figure 2.26 Wallasey School – section

Direct gain buildings as solar collectors

The Wallasey School building is a classic direct gain design. It has the essential features required for passive solar heating:

(1) a large area of south-facing glazing to capture the sunlight

(2) thermally heavyweight construction (dense concrete or brickwork). This stores the thermal energy through the day and into the night

(3) thick insulation on the outside of the structure to retain the heat.

After its construction, the oil-fired heating system originally installed was found to be unnecessary and was for a time removed, leaving the building totally heated by a mixture of solar energy, heat from incandescent lights and the body heat of the students.

Passive solar heating versus superinsulation

Although the Wallasey School building is one style of low-energy building, there are others. The Wates house, built at Machynlleth in Wales in 1975 (Figure 2.27) was one of the first 'superinsulated' buildings in the UK. It features 450 mm of wall insulation and small quadruple-glazed windows. This was a radical design, given that at this time normal UK houses were built with single glazing, no wall insulation, and new building regulations requiring a mere 25 mm of loft insulation were only just being introduced.

Figure 2.27 The superinsulated Wates House at Machynlleth

Situated low in a mountain valley, the Wates house is certainly not well-placed for passive solar heating. In fact, it was intended to be heated and lit by electricity from a wind turbine.

Which of the two design approaches – passive solar or superinsulation – is better? There are no easy answers to this question. The art of design for passive solar heating is to understand the energy flows in a building and make the most of them. There need to be sufficient solar gains to meet a substantial proportion of the winter heating needs. These can be reduced by good levels of insulation. Solar energy is also needed to provide adequate lighting, but not so much in summer that there is overheating.

Window energy balance

We can think of a south-facing window as a kind of passive solar heating element. Solar radiation enters during the day, and, if the building's internal temperature is higher than that outside, heat will be conducted, convected and radiated back out.

The question is whether more heat flows in than out, so that the window provides a net energy benefit. The answer depends on several things:

(1) the building's average internal temperature

(2) the average external temperature

(3) the available solar radiation

(4) the transmittance characteristics of the window, its orientation and shading

(5) the *U*-value of the window, which is, in turn, dependent on whether it is single or double glazed (or even better insulated).

Figure 2.28 shows the average monthly 'energy balance' of a south-facing window in the vicinity of London for a building with an average internal temperature of 18 °C. In the dull, cold months of December and January, a single-glazed window is a net energy loser and a double-glazed one only just breaks even. However, in the autumn and spring months, November and March, a double-glazed window becomes a positive contributor to space heating needs. Its performance can be further improved by insulating it at night.

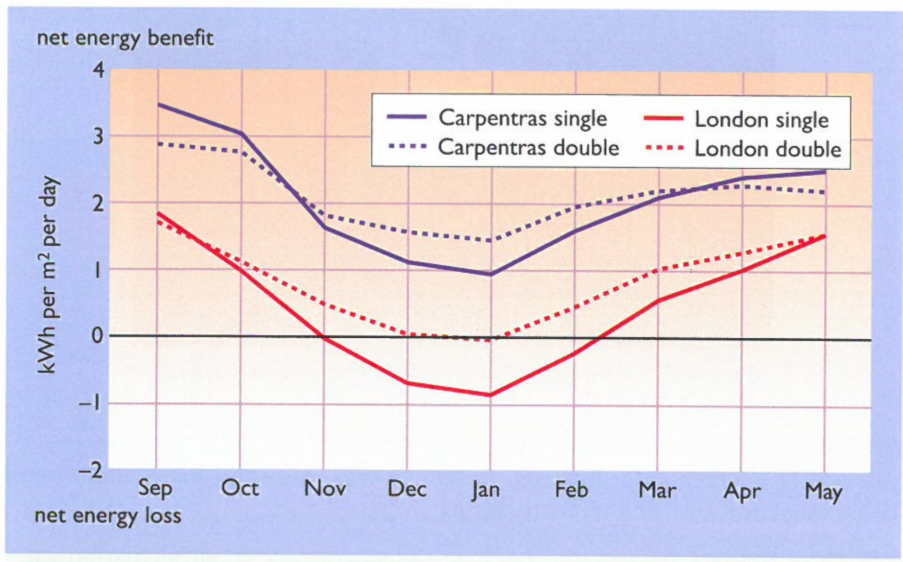


Figure 2.28 Window energy balance: London and Carpentras, in the south of France

We can compare this with a similar energy balance for Carpentras, near Avignon, in the south of France (also shown in Figure 2.28). Although the mid-winter months there are almost as cold as in London, they are far sunnier, being at a lower latitude. The incoming solar radiation is far greater than the heat flowing out, even in mid-winter, and the energy balance is markedly positive.

The heating season and free heat gains

To return to the UK, we need to consider how best use can be made of the solar energy available.

With a long heating season, a south-facing double-glazed window is a good thing. It can perhaps supply extra heat during October and November, March and April. On the other hand, with a very short heating season confined to the dullest months, say just December and January, it is not really much use at all.

How long is the heating season?

In order to answer this question, we must consider the rest of the building, its insulation standards and its so-called 'free' heat gains.

In a typical house, to keep the inside warmer than the outside air temperature, it is necessary to inject heat. The greater the temperature difference between the inside and the outside, the more heat needs to be supplied. In summer it may not be necessary to supply any heat at all, but in mid-winter large amounts will be needed. The total amount of heat that needs to be supplied over the year can be called the **gross heating demand**.

This will have to be supplied from three sources:

(1) 'free heat gains', which are those energy contributions to the space heating load of the building from the normal activities that take place in it: the body heat of people, and heat from cooking, washing, lighting and appliances. Taken individually, these are quite small. In total, they can make a significant contribution to the total heating needs. In a typical UK house, this can amount to 15 kWh per day

(2) passive solar gains, mainly through the windows

(3) fossil fuel energy, from the normal heating system.

Let us now consider, for example, the monthly average gross heat demand of a poorly insulated 1970s UK house (similar houses will be found right across northern and central Europe). As shown in Figure 2.29, this will

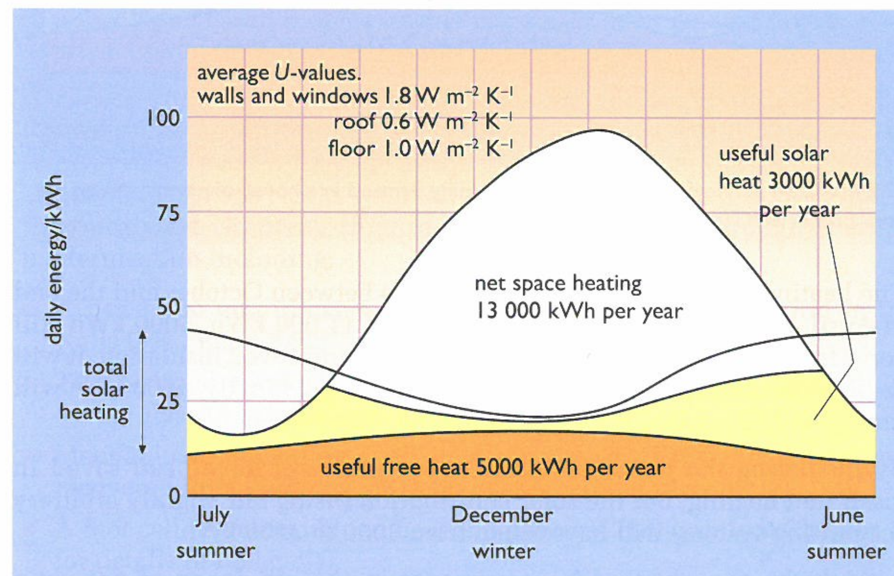


Figure 2.29 Contribution to the net space heating demand in a typical poorly insulated UK house of the 1970s

be higher in the cold mid-winter months than in the warmer spring and autumn. In summer, when the outside air temperature is high, this heating requirement almost drops to zero.

As shown in Figure 2.29, for this particular house, over the whole year, out of a total gross heating demand of 21 000 kWh, 5000 kWh come from free heat gains and 3000 kWh from solar gains (we have assumed to count free heat gains before solar gains).

Put another way, a perfectly ordinary house is already 14% passive solar heated. The **net heating demand**, to be supplied by the normal fossil fuel heating system, is simply the outstanding heat requirement, namely 13 000 kWh. This will have to be supplied from mid-September to the end of May.

It is possible to cut the house heat demand by putting in cavity wall and loft insulation and double instead of single glazing. This will reduce the gross heating demand and, as shown in Figure 2.30, allow the free heat gains and normal solar gains to maintain the internal temperature of the house for a longer period of the year. The insulation levels shown are approximately those of the 2002 UK Building Regulations for new housing. They have since been tightened further.

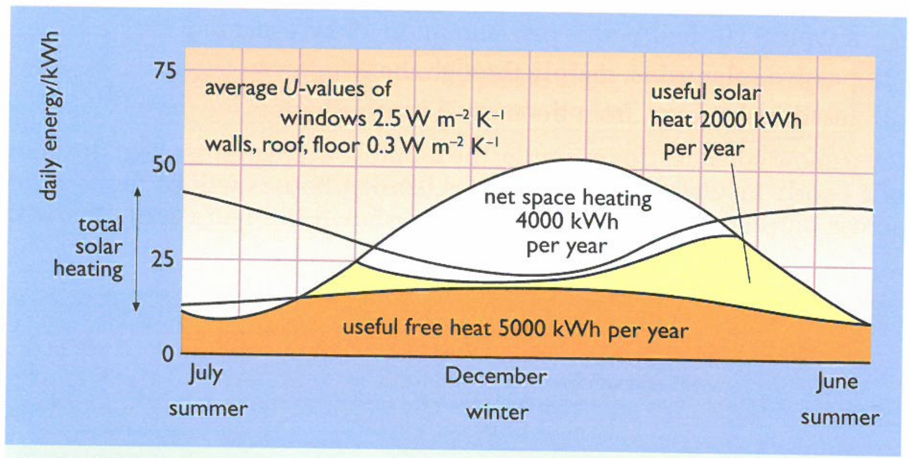


Figure 2.30 Contribution to net space heating demand in a house of normal design but reasonably well insulated

The heating season will then be reduced to between October and the end of April. Out of a total gross heat demand of 11 000 kWh, 5000 kWh still come from free heat gains, but as a result of the improved insulation, it will be possible to utilize only 2000 kWh of solar gains. Finally, 4000 kWh will remain to be supplied from the normal heating system.

By insulating the house, 9000 kWh per year will have been saved in fossil fuel heating, but the solar contribution (using our slightly arbitrary accounting system) will have fallen from 3000 to 2000 kWh.

It might be thought that improvements in the efficiency of domestic appliances and lighting would be leading to reduced levels of free heat gains from their use. UK statistics do show that in 2009 homes used less energy for cooking than they did in 1970, and that energy use for lighting and refrigerators has been falling since the late 1990s. However this has been more than offset by increased electricity use for consumer electronics, including televisions and home computers (DECC, 2011a). All of these unintentionally provide heating energy as well.

There are two ways in which the space heating demand could be cut further.

(1) By providing extra insulation. If the house was superinsulated, using insulation of 200 mm or greater thickness, the space heating load might disappear almost completely, leaving just a small need on the coldest, dullest days. Solar gains might not be essential.

(2) By providing appropriate glazing to ensure that the best use is made of the mid-winter sun.

Which of these methods is chosen will depend on the local climate and the relative expense of insulation materials and glazing. Per square metre, insulated wall tends to be a lot cheaper than good quality insulated glazing. The desired aesthetics of the building and the need for natural daylight inside will dictate whether or not it is easier to collect an extra 100 kWh of solar energy or to save 100 kWh with extra insulation.

Passivhaus design

In Germany the idea of superinsulation has been promoted in the form of the **PassivHaus standard**, developed during the 1990s. The house is 'passive' in the sense that it does not need a conventional large heating system (BRE, 2008). This form of design has been used in over 30 000 buildings across the world to date. It involves using thick insulation, good quality windows and airtight construction to reduce the space heating demand of a building to a low level. It can then be heated mainly by solar gains and heat from appliances and the occupants themselves.

Although the *Passivhaus* approach has mainly been applied to new buildings, even the thermal performance of existing buildings can be radically improved if they are adequately insulated. In the late 1990s an estate of apartment blocks originally built in the 1950s in Ludwigshafen in south-west Germany (Figure 2.31) was given a thorough thermal modernization including:

- At least 200 mm thickness of foam insulation on the roof and in the walls (see Figure 2.32)
- Triple-glazed windows with argon filling and low-emissivity coatings on the glass to cut the heat loss
- Mechanical ventilation with heat recovery (MVHR); this uses heat recovered from outgoing air to preheat incoming fresh air
- A fuel cell based combined heat and power (CHP) unit (see Chapter 10 for details of fuel cells).

Monitoring showed that the net space heating energy use (i.e. that to be supplied by the heating system) fell by a factor of seven from 210 kWh

31 The Brunck Estate in Ludwigshafen, Germany

Figure 2.32 Laying blocks of foam insulation on the roof

per square metre of floor area per year to only 30 kWh m^2 y^{-1}. 30 kWh is equivalent to the energy content of 3 litres of heating oil – hence the project name, the 3 Litre House (Luwoge, 2008).

General passive solar heating techniques

There are some basic general guidelines for optimizing the use of passive solar heating in buildings.

(1) They should be well-insulated to keep down the overall heat losses.

(2) They should have a responsive, efficient heating system.

(3) They should face south (anywhere from south-east to south-west is fine). The glazing should be concentrated on the south side, as should the main living rooms, with little-used rooms, such as bathrooms, on the north.

(4) They should avoid overshading by other buildings in order to benefit from the essential mid-winter sun.

(5) They should be 'thermally massive' to avoid overheating in summer.

These guidelines were used, broadly in the order above, to design some low-energy, passive solar-heated houses on the Pennyland estate in Milton Keynes in central England in the late 1970s. The design steps (see Figure 2.33) were carefully costed and the energy effects evaluated by computer model.

The resulting houses had a form that was somewhere between the Wallasey School building and the Wates house. The houses faced south, there was not too much glazing, but not too little, and the main living rooms were concentrated on the south side (see Figures 2.34–2.36).

An entire estate of these houses was built and the final product carefully monitored. At the end of the exercise it was found that the steps 1–5 listed

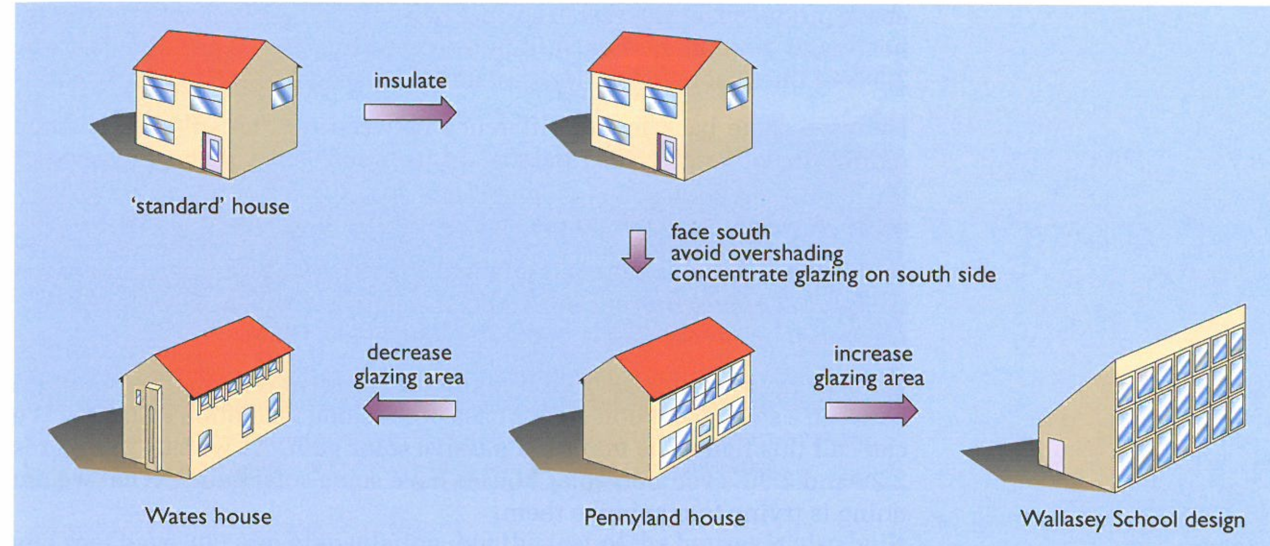


Figure 2.33 Design steps in low-energy housing

Figure 2.34 Passive solar housing at Pennyland – south elevation – the main living rooms have large windows and face south

Figure 2.35 Passive solar housing at Pennyland – the north side has smaller windows

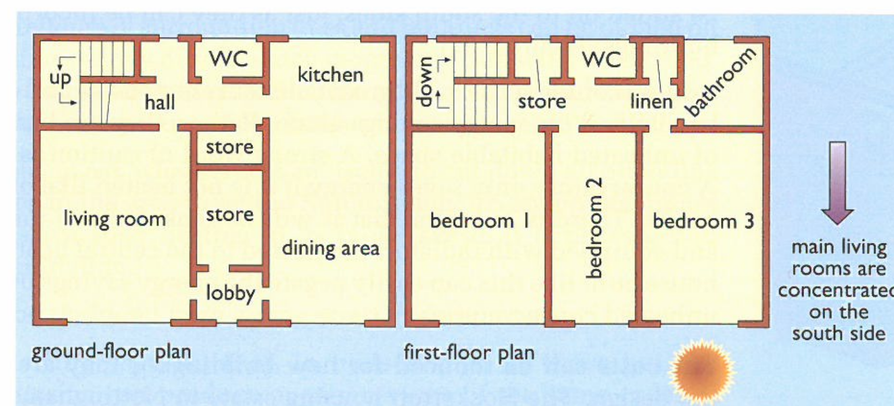


Figure 2.36 Pennyland floor plans

above produced houses that used only half as much gas for low-temperature heating as 'normal' houses built in the preceding year. The extra cost was 2.5% of the total construction cost and the payback time was four years.

Here we come back to the difference between the 'broad' and 'narrow' definitions of passive solar heating. In its broad sense, it encompasses all the energy-saving ideas (1–5 above) put into these houses. In its narrow sense, it covers only the points that are rigidly solar based (3–5).

In this project, insulation and efficient heating saved the vast bulk of the energy, but approximately 500 kWh per year of useful space heating energy came from applying points 3–5 (Chapman et al., 1985).

Put another way, this 500 kWh is the difference in energy consumption between a solar and a non-solar house of the same insulation standard. We can call this figure the **marginal passive solar gain**. As we saw in Figures 2.29 and 2.30, even non-solar houses have some solar gains. What we are doing is trying to maximize them.

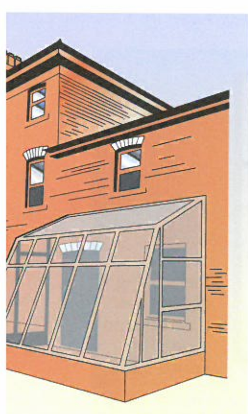
It is rather difficult to calculate the extra cost involved in producing marginal passive solar gains. After all, the passive solar 'heater' is an integral part of the building, not a bolt-on extra. Careful costing studies of different building designs and layouts have shown that modest marginal solar gains can be had at minimal extra cost.

Essentially, in its narrow sense, passive solar heating is largely free, being simply the result of good practice. In the 'wider' sense of integrated low-energy house design, the energy savings have to be balanced against the cost of a whole host of energy conservation measures, some of which involve glazing and perhaps have a solar element, and others which do not.

The balance between insulation savings and passive solar gains is also highly dependent on the local climate. In practice the most ambitious passive solar buildings are built in climates that have high levels of sunshine during cold winters.

Conservatories, greenhouses and atria

Direct gain design is really for new buildings: it cannot do much for existing ones. However, for many old buildings, conservatories or greenhouses could be added on to the south sides, just as they can be incorporated into new buildings (Figure 2.37).



.37 Conservatory on
1 terraced house

Add-on conservatories and greenhouses are expensive and cannot normally be justified on energy savings alone. Rather, they are built as extra areas of unheated habitable space. A strong word of caution is necessary here. A conservatory only saves energy if it is not heated like other areas of the house. There is a danger that it will be looked on as just another room and equipped with radiators connected to the central heating system. One house built like this can easily negate the energy savings of ten others with unheated conservatories.

The costs can be reduced for new buildings if they are integrated into the design. The Hockerton housing estate in Nottinghamshire in the UK, completed in 1998 (see Figure 2.38), combines a 'Wallasey school' type design with a full-width conservatory (EST, 2003). Not only do the walls

Figure 2.38 These low energy houses at Hockerton in Northamptonshire, completed in 1998, feature a full width conservatory, thick insulation and earth sheltering

and roof have 300 mm of insulation, but the rear of the houses is also built up with earth, giving extra thermal mass and protection from the worst winter weather. This is known as **earth sheltering**.

Glazed atria are also becoming increasingly common. At their simplest, they are just glazed-over light wells in the centre of office buildings. At the other extreme, entire shopping streets can be given a glazed roof, creating an unheated but well-lit circulation space. Again a strong word of caution is necessary. 'Heated' shops may have wide-open doors, or even entire frontages, onto the 'unheated' circulation space, giving rise to unnecessary heat losses.

Avoiding overshading

One important aspect of design for passive solar heating is to make sure that the mid-winter sun can penetrate to the main living spaces without being obstructed by other buildings. This will require careful spacing of the buildings.

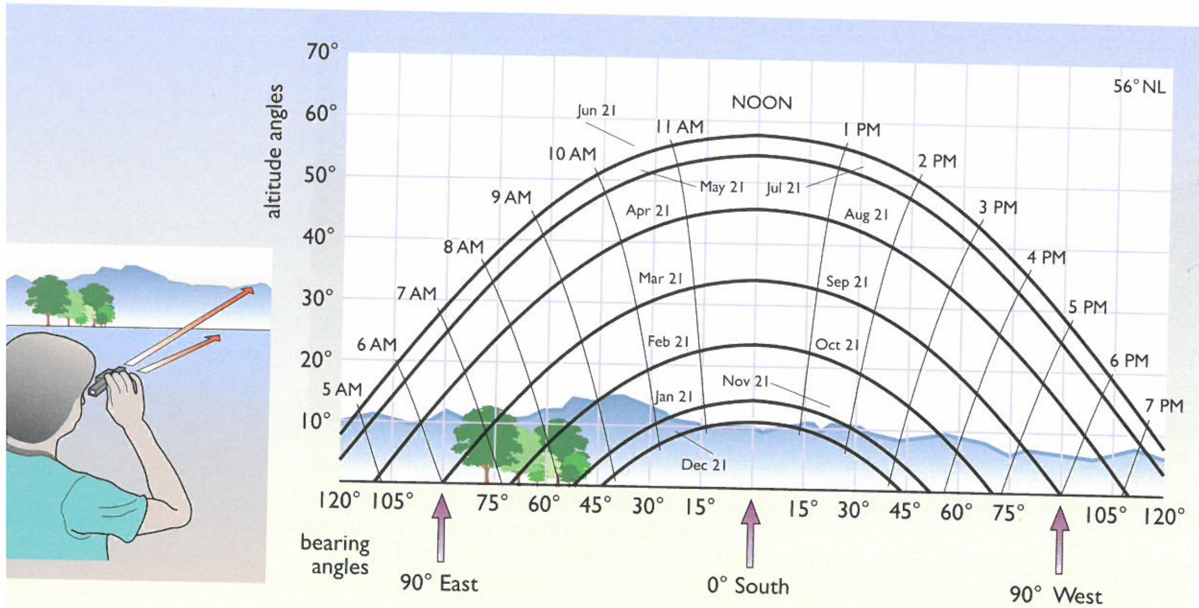
There are many design aids to doing this, but a useful tool is the **sunpath diagram** (see Figure 2.39). For a given latitude, this shows the apparent path of the Sun through the sky as seen from the ground.

In practice, the contours of surrounding trees and buildings can be plotted on it to see at what times of day during which months the Sun will be obscured. The Pennyland houses were laid out so that the midday sun in mid-December just appeared over the roof-tops of the houses immediately to the south.

However, we need to ask whether it is advisable to cut down all offending overshading trees in the area to let the Sun through. To obtain maximum benefit from passive solar heating in its broad sense, it is necessary to follow another guideline:

Houses should be sheltered from strong winter winds.

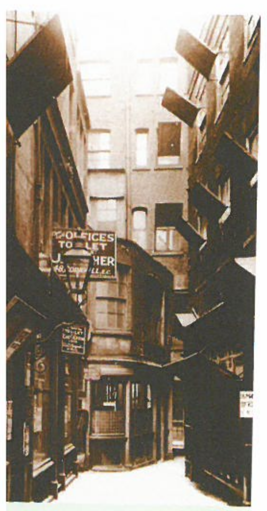
Computer modelling suggests that, in houses such as those built at Pennyland, sheltering can produce energy savings of the same order of magnitude as marginal passive solar gains, approximately 500 kWh per year per house.



2.39 Plotting the skyline on a sunpath diagram can give important information about overshading. The sunpath diagram ; for 56° N, which is approximately the latitude of Glasgow or Edinburgh

Where do the winter winds come from? This is immensely dependent on the local micro-climate of the site. In large parts of the UK, the prevailing wind is from the south-west. It would thus be ideal if every house could have a big row of trees on its south-west side. But is it possible to provide shelter from the wind without blocking out the winter sun? This is where housing layout becomes an art. Every site is different and needs solutions appropriate to it.

2.8 Daylighting



40 Mirrors used to able daylight in narrow reets before the orld War

As well as providing heat, the Sun provides daylight. This is a commodity that we all take for granted. Replacing it with artificial light was, before the middle of the 20th century, very expensive (a topic discussed in Everett et al., 2012). Large mirrors were used in narrow London city streets to gather valuable daylight (Figure 2.40). With the coming of cheap electricity and efficient fluorescent lighting, daylight has been neglected and most modern office buildings are designed to rely heavily on electric light.

Houses are traditionally well-designed to make use of natural daylight. Indeed, most of those that were not have long ago been designated slums and duly demolished. In the UK in 2010, domestic lighting accounted for only 2.6% of the sector's delivered energy use.

In some commercial offices, however, lighting can account for up to 30% of the delivered energy use. Modern factory units and hypermarket buildings are built with barely any indows. Modern 'deep-plan' office buildings, such as those at Canary Wharf in London (Figure 2.41), have plenty of windows on the outside but there are many offices, central corridors and stairwells on the inside that require continuous lighting, even when the Sun is shining brightly outside.

Although in winter the heat from lights can usefully contribute to space heating energy, in summer (when there is most light available) it can cause overheating, especially in well-insulated buildings. Making the best use of natural light saves both on energy and on the need for air conditioning.

Daylighting is a combination of energy conservation and passive solar design. It aims to make the most of the natural daylight that is available. Many of the design details will be found in the better quality 19th century buildings. Traditional techniques include:

- shallow-plan design, allowing daylight to penetrate all rooms and corridors
- light wells in the centre of buildings
- roof lights
- tall windows, which allow light to penetrate deep inside rooms
- the use of task lighting directly over the workplace, rather than lighting the whole building interior.

Figure 2.41 Modern deep-plan office buildings, such as those at Canary Wharf in London, require continuous artificial lighting in the centre, which may create overheating in summer

Other experimental techniques include the use of steerable mirrors to direct light into light wells, and the use of optical fibres and light ducts.

When artificial light has to be used, it is important to make sure that it is used efficiently and is turned off as soon as natural lighting is available. Control systems can be installed that reduce artificial lighting levels when photoelectric cells detect sufficient natural light. Payback times on these energy conservation techniques can be very short and savings of 50% or more are feasible.

In designing new buildings, there is a conflict between lighting design and thermal design. Deep-plan office buildings have a smaller surface area per unit volume than shallow-plan ones. They will need less heating in winter. As with all architecture, there are seldom any simple answers and compromises usually have to be made.

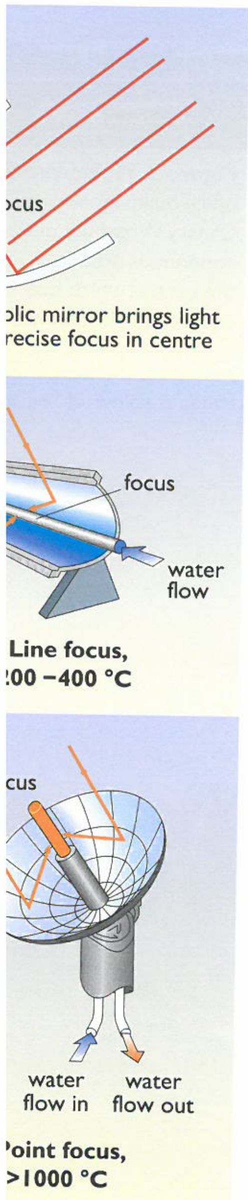
2.9 Solar thermal engines and electricity generation

So far, we have considered only low-temperature applications for solar energy. If the Sun's rays are concentrated using mirrors, high enough temperatures can be generated to boil water to drive steam engines. These can produce mechanical work for water pumping or, more commonly nowadays, for driving an electric generator. This solar thermal-electric generation is known as **concentrating solar power (CSP)**.

The systems used have a long history and many modern plants differ little from the prototypes built 100 years ago. Indeed, if cheap oil and gas had not appeared in the 1920s, solar engines might have developed to be commonplace in sunny countries.

Concentrating solar collectors

Legend has it that in 212 BC Archimedes used the reflective power of the polished bronze shields of Greek warriors to set fire to Roman ships



2 Parabolic mirrors
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besieging the fortress of Syracuse. Although long derided as myth, Greek navy experiments in 1973 showed that 60 men each armed with a mirror 1 m by 1.5 m could indeed ignite a wooden boat at 50 m.

If each mirror perfectly reflected all its incident direct beam radiation squarely on to the same target location as the other 59 mirrors, the system could be said to have a **concentration ratio** of 60. Given an incident direct beam intensity of, say, 800 W m^{-2}, the target would receive 48 kW m^{-2}, roughly equivalent to the power density of a boiling ring on an electric cooker.

This use of steerable mirrors forms the basis of the modern 'power tower' systems described later.

The most common method of concentrating solar energy is to use a parabolic mirror. All rays of light that enter parallel to the axis of a mirror formed in this particular shape will be reflected to one point, the focus (Figure 2.42(a)). However, if the rays enter slightly off-axis, they will not pass through this point. It is therefore essential that the mirror tracks the Sun.

In the *line focus or trough collector* the Sun's rays are focused onto a pipe running down the centre of a trough (Figure 2.42(b)). The pipe is likely to carry a high temperature heat transfer fluid such as a mineral oil. Such systems are mainly used for generating steam for electricity generation. The trough can be pivoted to track the Sun up and down (i.e. in **elevation**) or east to west. A line focus collector can be oriented with its axis in either a horizontal or a vertical plane.

In the *point focus or dish collector*, the Sun's image is concentrated on a steam boiler or a Stirling engine in the centre of the mirror. For optimum performance, the axis must be pointed directly at the Sun at all times, so it needs to track the Sun both in elevation and in **azimuth** (that is, side to side).

Most mirrors are assembled from sheets of curved or flat glass fixed to a framework.

There are trade-offs between the complexity of design of a concentrating system and its concentration ratio. A well-built and well-aimed parabolic dish collector can achieve a concentration ratio of over 1000. A line focus parabolic trough collector may achieve a concentration ratio of 50, but this is adequate for most power plant systems. The ratio required depends on the desired target temperature.

Unless the incident solar energy is carried away by some means, the target, be it a boat or a boiler, will settle at an equilibrium temperature where the incoming radiation balances heat losses to the surrounding air. The latter will be mainly by convection and re-radiation of infrared energy and will be dependent on the surface area of the target and its exposure to wind. A line focus parabolic trough collector can produce a temperature of 200–400 °C. A dish point focus system can produce a temperature of over 1500 °C.

What is important to appreciate is that no concentrating collector can deliver in total any more energy than falls on it, but what it does receive is all concentrated into one small area.

The first solar engine age

The process of converting the concentrated power of the Sun into useful mechanical work started in the 19th century. When, in the 1860s, France lacked a supply of cheap coal, Augustin Mouchot, a mathematics professor from Tours, had the answer: solar-powered steam engines. In the 1870s and 1880s, Mouchot and his assistant, Abel Pifre, produced a series of machines ranging from the solar printing press shown in Figure 2.43 to solar wine stills, solar cookers and even solar engines driving refrigerators.

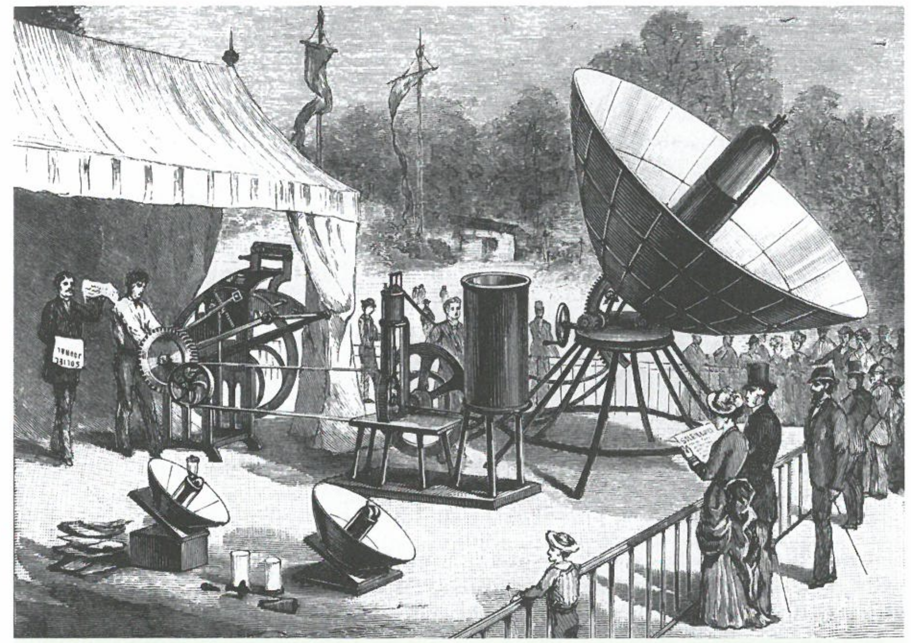


Figure 2.43 Abel Pifre's solar-powered printing press

Their basic collector design was a parabolic concentrating collector with a steam boiler mounted at the focus. Steam pipes ran down to a reciprocating engine (like a steam railway engine) on the ground.

Although these systems were widely acclaimed, they suffered from the fundamental low-power density of solar radiation and low overall efficiency.

In order to understand some of the problems of engines powered by solar energy, it is necessary to consider the Second Law of Thermodynamics (see Box 2.4).

The early French solar steam engines were not capable of producing steam at really high temperatures and as a result their thermal efficiencies were poor. It required a machine that occupied 40 m^2 of land just to drive a one-half horsepower engine (less than the power of a modern domestic vacuum cleaner!)

By the 1890s, it was clear that this was not going to compete with the new supplies of coal in France, which were appearing as a result of increased investment in mines and railways.

BOX 2.4 Heat engines and Carnot efficiency

The steam engine is familiar enough. It works by boiling water to produce a high-pressure vapour. This then goes to an 'expander', which extracts energy and from which low-pressure vapour is exhausted. The expander can be a reciprocating engine or a turbine. Such systems are known as **heat engines**.

All heat engines are subject to fundamental limits on their efficiency set by the **Second Law of Thermodynamics** (a topic discussed in more detail in Everett et al., 2012). They all produce work by taking in heat at a high temperature, T_{in}, and rejecting it at a lower one, T_{out}. In the ideal case, the maximum efficiency they could be expected to achieve is given by:

$$\text{maximum efficiency} = 1 - \frac{T_{out}}{T_{in}}$$

where T_{in} and T_{out} are expressed in the Kelvin temperature scale (or degrees Celsius plus 273). This ideal efficiency is known as the **Carnot efficiency**, after the 19th century French scientist Sadi Carnot.

For example, in a modern CSP plant well-designed parabolic trough collectors might produce steam at 350 °C. This would be fed to a steam turbine and low-temperature heat would be rejected in cooling towers at 30 °C. The theoretical efficiency of the system would therefore be:

$$1 - (30 + 273)/(350 + 273) = 0.51$$

i.e. 51%.

Its practical efficiency is more likely to be about 25%, due to various losses.

Systems that use turbines are often referred to as **Rankine cycles**, after another pioneer of thermodynamics, William Rankine.

Normally, to boil water, its temperature must be raised to at least 100 °C. This may be difficult to achieve with simple non-concentrating solar collectors or with other sources of heat. It would be more convenient to work with a fluid with a lower boiling point. In order to do this, a 'closed cycle' system must be adopted, with a condenser that changes the exhaust vapour back to a liquid and allows it to be returned to the boiler.

Systems have been developed that use stable organic chemicals with suitably low boiling points, similar to the refrigerants used in heat pumps (see Box 2.3). One that uses an organic fluid and a turbine is known as an **organic Rankine cycle (ORC)**. These are commonly used with low-temperature solar engines such as ocean thermal energy conversion (OTEC) systems, described later, and some types of geothermal plant as described in Chapter 9.

These low-temperature systems are likely to have poor efficiencies. For example, the theoretical Carnot efficiency of a heat engine that was fed with relatively low-temperature vapour at 85 °C, say from a flat plate solar collector, and exhausted heat at 35 °C would be only 14%.

At the beginning of the 20th century, in the USA, an entrepreneur named Frank Shuman applied the principle again, this time with large parabolic trough collectors. He realized that the best potential would be in really sunny climates. After building a number of prototypes, he raised enough financial backing for a large project at Meadi in Egypt. This used five parabolic trough collectors, each 80 m long and 4 m wide. At the focus, a finned cast iron pipe carried away steam to an engine.

In 1913, his system, producing 55 horsepower, was demonstrated to a number of VIPs, including the British government's Lord Kitchener. The payback time would have been only four years since the alternative fuel in Egypt at the time was coal, which had to be imported from the UK.

By 1914, Shuman was talking of building 20 000 square miles of collector in the Sahara, which would 'in perpetuity produce the 270 million horsepower required to equal all the fuel mined in 1909' (see Butti and Perlin, 1980, for the full story). Then came the First World War and immediately afterwards the era of cheap oil. Interest in solar steam engines collapsed and lay dormant for virtually half a century.

The new solar age

Solar engines revived with the coming of the space age. When, in 1945, a UK scientist and writer, Arthur C. Clarke, described a possible future 'geostationary satellite', which would broadcast television to the world, it was to be powered by a solar steam engine. In fact, by the time such satellites materialized, 25 years later, photovoltaics (see Chapter 3) had been developed as a reliable source of electricity.

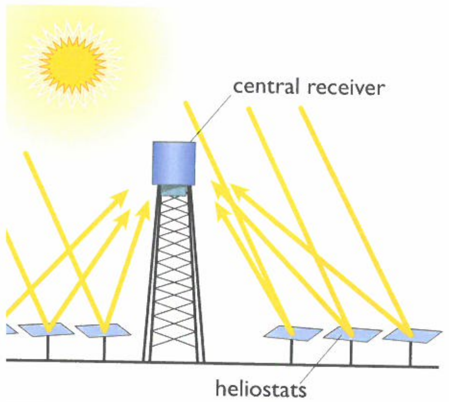
Elsewhere, space rockets, guided missiles and nuclear reactors needed facilities where components could be tested at high temperatures without contamination from the burning of fuel needed to achieve them. The French solved this problem in 1969 by building an eight-storey-high parabolic mirror at Odeillo in the Pyrenees. This faced north towards a large field of **heliostats:** steerable flat mirrors, which, like those held by Archimedes' warriors, track the Sun. This huge mirror could produce temperatures of 3800 °C at its focus, but only in an area of 50 cm^2.

Power towers

In the early 1980s, the first serious, large, experimental solar thermal electricity generation schemes were built to make use of high temperatures. These are now known as concentrating solar power (CSP) plants. Several were of the 'power tower' type, using a large array of heliostats on the ground which focus the Sun's rays onto a central receiver at the top of a tower (Figure 2.44). This is a chamber where either steam can be produced directly, or a heat transfer fluid such as mineral oil or molten salt can be raised to a high temperature to be pumped away to generate steam at ground level. The steam is then used to drive a turbine to generate electricity.

A 10 megawatt (MW) plant, *Solar One*, was built at Barstow in California in 1981. Initially the Barstow plant used high-temperature synthetic oils to carry away the heat to a steam boiler. In 1995, it was rebuilt as Solar Two, and between 1996 and 1999 it operated using a molten salt at over 500 °C (this involved a mixture of sodium nitrate and potassium nitrate that has a melting point of over 200 °C). Its design included heat storage, allowing it to produce electricity potentially on a 24-hour basis.

More recently this technology has been taken up near Seville in southern Spain, where two plants have been commissioned, the 11 MW *Planta Solar* 10 (PS10) in 2007 and the adjacent *Planta Solar* 20 (PS20) in 2009 (Figure 2.45). These have limited heat storage and can use natural gas



2.44 The central receiver on a power
; heated by a large array of steerable
t mirrors on the ground

Figure 2.45 The PS10 and PS20 power tower plants near Seville in Spain

as back-up. The newer *Gemasolar* 20 MW plant also near Seville and commissioned in 2011 has increased thermal storage using molten salt.

Parabolic trough concentrating collector systems

Until very recently most of the world's electricity produced by solar thermal generation came from several large solar power stations developed by Luz International in the Mojave desert in California. Between 1984 and 1990, Luz constructed nine Solar Electricity Generating Systems (SEGS) of between 13 and 80 MW rating and totalling 354 MW. These are essentially massively uprated versions of Shuman's 1913 design, using large fields of parabolic trough collectors (see Figures 2.46 and 2.47). Each successive project has concentrated on increasing economies of scale in purchasing mirror glass and the use of commercially available steam turbines. The last 80 MW SEGS to be built (SEGS IX) has 484 000 m^2 of collector area.

.46 SEGS solar collector field at Kramer Junction in southern California

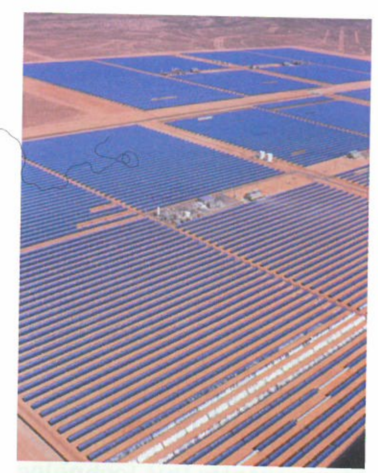


Figure 2.47 SEGS solar collector field – aerial view

The collectors heat synthetic oil to 390 °C, which can then produce high-temperature steam via a heat exchanger. In recent years the five plants at Kramer Junction (SEGS III to VII) have recorded annual plant efficiencies of 14% and peak efficiencies of up to 21.5% (Solarpaces, 2010). This is competitive with commercially available PV systems.

The SEGS plants were intended to compete with fossil fuel generated electricity to feed the peak afternoon air-conditioning demands in California, and for several years this objective was successfully achieved. In 1992, reductions in the price of gas, to which the price paid for electricity from the plant was tied, brought financial difficulties for the Luz company and the construction of new plants ceased. However those already built have continued to operate reliably and cheaply and this is now regarded as a 'mature technology'. The construction of large solar power plants resumed in the USA in 2007 with the commissioning of *Nevada Solar One*, a 64 MW parabolic trough plant outside Boulder City, Nevada.

Concerns of global warming have meant that the state of California has set a target of having 33% of its electricity from renewable sources by 2020. This has led to proposals for over 4 GW of concentrating solar projects, most of them large parabolic trough systems. Some of the proposed plants are solar-fossil fuel hybrids where the steam turbine is powered by the Sun during the day, by stored heat in the evening and by natural gas at night. There are good thermodynamic reasons for combined gas and solar operation, since it allows the steam turbine to be run at its maximum operating temperature and thermal efficiency.

Fresnel mirror systems

Fresnel mirror systems are a halfway house between power tower and parabolic trough designs. A raised linear collector is heated by steerable strips of flat mirror. Although this has limited temperature-raising performance it only requires ground-mounted flat mirrors and could potentially be cheaper than parabolic trough systems. A prototype 5 MW plant started operation in 2008 near Bakersfield in California.

Parabolic dish concentrator systems

Instead of conveying the solar heat from the collector down to a separate engine, an alternative approach is to put the engine itself at the focus of a mirror. This has been tried both with small steam engines and with Stirling engines.

Stirling engines are described in Everett et al., 2012, and have a long history (they were invented in 1816). Although steam engines have fundamental difficulties when operating with input temperatures above 700 °C, Stirling engines, given the right materials, can be made to operate at temperatures of up to 1000 °C, with consequent higher efficiencies. Current experimental solar systems using these have managed very high overall conversion efficiencies, approaching 30% on average over the day.

A pilot scheme of 60 dishes each driving a 25 kW Stirling engine was constructed in Arizona in 2010 (Figure 2.48) though it is not clear whether

Figure 2.48 An array of 60 parabolic dishes each with a 25 kW Stirling engine constructed at Maricopa in Arizona in 2010

or not further proposed multi-megawatt projects requiring many hundreds of dishes will go ahead.

Low-temperature systems

The systems above rely on producing high temperatures. As described in Box 2.4 this is essential to maximize generation efficiency. It also minimizes the land area required for a given power output. However, other low-temperature systems have been tried and remain of interest.

Solar ponds

Solar ponds use a large, salty lake as a kind of flat plate collector. If the lake has the right gradient of salt concentration (salty water at the bottom and fresh water at the top) and the water is clear enough, solar energy is absorbed at the bottom of the pond.

The hot, salty water cannot rise, because it is heavier than the fresh water on top. The upper layers of water effectively act as an insulating blanket and the temperature at the bottom of the pond can reach 90 °C. This is a high enough temperature to run an organic Rankine cycle (ORC) engine. However, the thermodynamic limitations of the relatively low temperatures mean low solar-to-electricity conversion efficiencies, typically less than 2%. Nevertheless, a system of 5 MW peak electrical output, fed from a lake of over 20 hectares, was demonstrated in Israel in the 1980s. The large thermal mass of the pond acts as a heat store, and electricity generation can go on day or night, as required. Their best location is in the large areas of the world where natural flat salt deserts occur.

In practice, the system has disadvantages. Large amounts of fresh water are required to maintain the salt gradient. These can be hard to find in the

solar pond's natural location, the desert. Indeed, the best use for solar ponds may be to generate heat for water desalination plants, creating enough fresh water to maintain themselves and also supply drinking water.

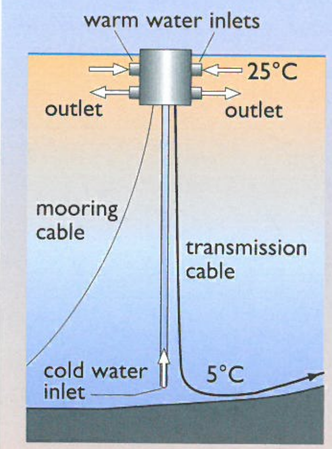


Figure 2.49 Ocean Thermal Energy Converter (OTEC) floating platform

Ocean thermal energy conversion (OTEC)

Ocean thermal energy conversion essentially uses the sea as a solar collector. It exploits the small temperature difference between the warm surface of the sea and the cold water at the bottom (Figure 2.49). In deep tropical waters, 1000 m deep or more, this can amount to 20 °C, which is sufficient to drive an ORC engine.

Although the efficiency is likely to be low and the ORC system used needs to be finely tuned to boil at just the right temperature, there is an extremely large amount of water available. The technology is of considerable interest on islands that have to import fuel for electricity generation.

Initial experiments made on a ship in the Caribbean in the 1930s were only marginally successful. Water had to be pumped from a great depth to obtain a significant temperature difference, and the whole system barely produced more energy than it used in pumping. In the 1970s a more successful 50 kW OTEC device was tested in Hawaii by the US Lockheed Martin company. In 2009 the US Navy awarded the company a US$9 million contract to continue the research in conjunction with the University of Hawaii.

The engineering difficulties are enormous. An OTEC station producing 10 MW of electricity would need to pump nearly 500 cubic metres per second of both warm and cold water through its heat exchangers, whilst remaining moored in sea 1000 metres deep.

Solar updraft tower devices

These exploit warm air produced in a very large greenhouse. The air is allowed to rise through a tall chimney. Solar updraft towers are sometimes referred to as 'solar chimneys', but this term may also be used to refer to devices using rising warm air to ventilate buildings.

The updraft is used to turn an air turbine at the base of the chimney, driving a generator to produce electricity. This sounds simple enough. What is not so simple is the scale of construction. A 50 kW prototype built in Manzanares in Spain in 1981 (Figure 2.50) and operational until 1989 used a greenhouse collector 240 m in diameter feeding warm air to a chimney 195 m high.

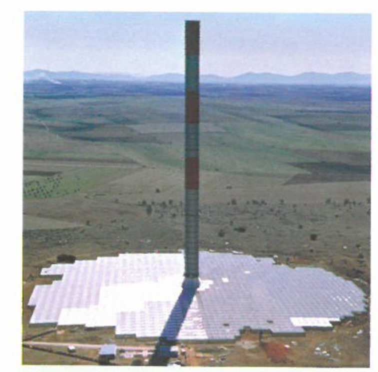


Figure 2.50 This prototype 50 kW solar updraft tower at Manzanares in Spain operated between 1981 and 1989

There are large economies of scale to be had. In a very sunny region of the world, a cost-optimum plant might have an output of 100 MW using a collector 3.6 km in diameter and feeding a chimney 950 m tall (Schlaich, 1995). However, because such design only produces warm air (a 35 °C temperature rise has been assumed in the calculations) the overall generation efficiency would be low, around 1.3%. Such a system would thus require considerably more land area than one of equivalent output using high-temperature concentrating collectors. However the ground beneath the collector provides a limited amount of energy storage, extending the output by a couple of hours into the evening.

A 200 kW prototype has been constructed at Jinshawan in Inner Mongolia in China and there are proposals for multi-megawatt plants in a number of countries.

2.10 Economics, potential and environmental impact

Although the motto of Bailey's 'Day and Night' Solar Water Heater company was 'Solar energy, like salvation, is free' the company still had to charge its customers money for the collection equipment. Fortunately, the assessment of the economics of solar thermal systems doesn't pose any great problems. Most solar thermal heating systems can be regarded in the same manner as conventional heating plant or building components and simple notions of 'payback times' often give an adequate assessment (see Appendix B). Solar thermal electricity plants have similar ratings and life expectancies to gas or diesel power stations. The difference is that they have no fuel costs and reasonably low operating and maintenance costs.

Domestic active solar water heating

In terms of collector area, domestic water heating for residential buildings makes up the bulk of the world solar thermal market. In 2010 the UK had an estimated '**solar park**' (i.e. total installed area) of approximately 570 000 m^2 of glazed and evacuated tube collectors (ESTIF, 2011). This represents an almost fourfold increase since 2001. However the figure contrasts with the 13 million m^2 installed in Germany.

It is likely that 50% of existing UK dwellings are suitable to have a solar water heater fitted. If this potential were to be fully taken up by 2025, this would require the deployment of approximately 12 million systems (allowing for a rise in the UK housing stock), or about 50 million m^2 of collectors. This could save an estimated 34.6 PJ (9.6 TWh) per year of oil and gas and 2.4 TWh per year of electricity, resulting in reductions of about 1% of current UK CO_2 emissions (DTI, 1999).

The same DTI study suggested that there were only about 100 000 swimming pools in the UK, and even if this number were to double by 2025, the total potential energy saving from the use of solar heating would only amount to an extra 7% over and above that for domestic water heating.

At the time of writing (2011), sales of solar water heaters in the UK are low and prices are high. According to the Energy Saving Trust (EST), the typical cost of an installed solar water heater in the UK is £4800. They estimate that, based on the results of a recent field trial (EST, 2011a), typical savings from a well-installed and properly used system are £55 per year when replacing gas heating and £80 per year when replacing electric immersion heating. They also estimate the typical carbon savings at around 230 kg CO_2 y^{-1} when replacing gas and 510 kg CO_2 y^{-1} when replacing electric immersion heating (EST, 2011b).

This gives a payback time of 87 years against gas and 60 years against electricity. This might not seem encouraging. However, the savings in

CO_2 emissions can be given a financial value, a 'carbon price' reflecting the reduced damage to the environment (a topic discussed a little further in Chapter 10, Section 10.3. Taking a value of £40 per tonne of CO_2 improves the payback time to 75 years against gas and 48 years against electricity.

As pointed out earlier, solar collectors are in competition with other energy saving devices such as heat pumps (although these do require considerable amounts of electricity for their operation). The UK Committee on Climate Change (CCC) estimates that the levelized cost of heat from solar thermal panels for domestic use is nearly 27 p kWh^{-1} (see Appendix B for an explanation of 'levelized cost'). This compares with values of 6.8–10.5 p kWh^{-1} for heat from a conventional gas boiler (including the costs of the boiler itself) and 10.9–18.6 p kWh^{-1} for heat from heat pumps (CCC, 2011).

Looking further afield, the economics are more promising. In central and southern Europe solar thermal heat may be cost competitive with both gas and electricity (ESTTP, 2009). In southern Europe there is more sunshine, so a system may produce twice as much energy per square metre of collector as in the UK. It is perhaps not surprising that Greece has a high level of solar water heater ownership and that sales have been running at 150 000–200 000 m^2 y^{-1}.

But it is somewhat surprising that Greece was overtaken in 1999 in terms of collector area per head of population by Austria. Between 1995 and 1998 the rate of installation there was running at around 200 000 m^2 y^{-1} and this rose to about 350 000 m^2 y^{-1} in 2008 and 2009 (ESTIF, 2011). Much of the initial popularity of solar water heating was attributable to the success of 'do-it-yourself' schemes.

In Europe and its associated (EU-27) states sales of solar collectors more than tripled between 2000 and 2010, the main countries being Germany, Austria, France, Greece, Italy and Spain.

Looking further afield, China has almost 60% of the world's installed capacity (over 100 GW of peak thermal capacity in 2009). Over 90% of these are thermosyphon systems and use evacuated tubes (see Figure 2.51) (Weiss and Mauthner, 2011). Volume manufacture and competition between many suppliers means that collector prices are typically a third of those for systems outside China (IPCC, 2011).

Figure 2.51 A typical Chinese solar water heater using evacuated tube collectors

As for environmental impact, that of solar water heating schemes in the UK is likely to be small. The materials used are those of everyday building and plumbing. Pumped solar collectors can be installed to be visually almost indistinguishable from normal roof lights, with storage tanks hidden inside the roof space. Elsewhere, the use of free-standing thermosyphon systems on flat roofs can be highly visually intrusive. It is not so much the collector that is the problem but the storage tank above it. (Bailey's 'Day and Night' Solar Water Heater Company also had to face these problems. It offered to disguise the storage tank as a chimney.)

The situation is perhaps a little different for the kind of large district heating array shown in Figure 2.24 which obviously takes up a significant amount of urban ground area that could be used for other purposes.

Passive solar heating and daylighting

In its narrow sense of producing an increase in the amount of solar energy directly used in providing useful space heating, passive solar heating is highly economic, indeed possibly free. It should be borne in mind that to some extent passive solar heating and the use of daylight are already features of normal buildings, reducing the UK's energy demand by an estimated 0.5 EJ (DECC, 2011b). This is a figure that does not appear in national renewable energy statistics.

Buildings specifically designed to use passive solar heating have been generally well-received by their occupants and are of interest to architects. However, the potential is limited by the low rate of replacement of the building stock.

In it broader, *Passivhaus,* sense of reducing overall heating energy demand, including retrofit projects, the potential is enormous. Yet, perversely, the superinsulation of buildings that contain large numbers of heat-producing appliances is likely to reduce the heating season to the dull mid-winter months, making the use of solar energy less important.

Designing buildings to take advantage of daylighting involves both energy conservation and passive solar heating considerations. In warmer countries, daylighting may be far more important, since cutting down on summer electricity use for lighting can also save on air conditioning costs.

Designing and laying out buildings to make the best use of sunlight has been part of the architectural tradition for centuries. It is generally seen as environmentally beneficial and has already shaped many towns and cities. For example, when in 1904 the city council of Boston, Massachusetts, USA, was faced with proposals for a 100 m high skyscraper, it commissioned an analysis of the shading of other buildings that this would cause. It was not pleased with the results and imposed strict limits on building heights.

However, a word of caution is necessary. In the UK, the tradition of new town development has been based partly on Victorian notions of the health aspects of 'light and air' in contrast to the overcrowded squalor of existing cities. This has been beneficial in terms of better penetration of solar energy into buildings. On the other hand, the encouragement of low building densities has led to vast tracts of sprawling suburbs and the consumption of enormous quantities of energy in transportation.

Solar thermal engines and electricity generation

As the original pioneers realized, it pays to build solar thermal power systems in really sunny places. In order to generate the high temperatures necessary for thermodynamically efficient operation, the local climate has to have plenty of direct solar radiation – diffuse radiation will not do. Although there was a surge of interest in solar thermal electricity in the 1980s, low fossil fuel prices around the world dampened interest during the 1990s – in contrast to continued enthusiasm for photovoltaics. It is only since about 2005 that construction of new solar thermal power plants has revived and there are now several gigawatts of plant under construction around the world.

Currently, in sunny desert locations, solar thermal electricity, particularly that from large parabolic trough plants, is considered competitive with large-scale PV power. The technology also has potential for thermal heat storage and integration with conventional fossil-fuelled steam power plants. In the USA, the cost of electricity from parabolic trough plants without heat storage is estimated to be around 17 to 20 US cents per kWh (10.6 to 12.5 pence per kWh) (Solarpaces, 2010). The bulk of this cost consists of repayments on the initial capital investment. Operation and maintenance costs are a modest 3 cents per kWh (2 pence per kWh) (Greenpeace/ESTELA/Solarpaces, 2009).

If six hours of heat storage is included then the price rises to 20 to 30 US cents per kWh (12.5 to 18.8 p per kWh) (IPCC, 2011). Although this technology could not compete with cheap natural gas in the USA in the 1990s, its economics (and low CO_2 emissions) are sufficiently good to support a resurgence of construction in the USA and in countries such as Spain.

The overall potential for such systems is enormous. Back in 1914, Frank Shuman was talking of building 20 000 square miles (50 000 km^2) of collector in the Sahara desert. With modern concentrating solar power plant 1 km^2 of land is enough to generate as much as 100–130 GWh of electricity per year (Greenpeace/ESTELA/Solarpaces, 2009). Ignoring the relative availability over the year, 3000 km^2 would thus be adequate to supply all of the UK's electricity and 35 000 km^2 (about 12% of the area of the state of Nevada) sufficient to supply all of the USA's electricity.

Sunny deserts, within striking distance of large urban electricity demands, are needed. In California, the Mojave desert is ideal. In Europe, central and southern Spain and other southern Mediterranean countries are possibilities, with proposals for grid links to North Africa (see Chapter 10, Section 10.8).

The problem would be to find a suitable way of conveying the output to the loads. Although long-distance electricity transmission can be used, the manufacture and distribution of hydrogen might be another possibility. The possibilities of a future 'hydrogen economy' are discussed in Chapter 10.

The environmental consequences of solar thermal power stations are somewhat mixed. A major problem is the sheer quantity of land required. Although, typically, the collectors only take up one-third of the land area, it may be physically difficult to use it for anything else. This is unlike wind farms where the turbines are very widely spaced and crops can grow underneath. CSP plants also require a certain amount of water for washing dust off the mirrors. This may be hard to come by in desert locations.

Solar ponds and solar thermal updraft projects need even larger areas of flat land than CSP plants because of their low thermodynamic efficiency.

The environmental consequences of OTEC systems may be mixed. On the one hand, it is claimed that the vast amounts of water being pumped circulate nutrients and can increase the amount of fish life. On the other, dissolved carbon dioxide can be released from the deep sea water, thereby negating some of the benefits of renewable energy generation. Only further experiments will resolve these issues.

2.11 Summary

Solar energy is a resource that is there for the taking. All that is needed is to produce the necessary hardware.

This chapter started by introducing the most basic 'active solar' technology: the rooftop solar water heater. Although this has limited potential in the UK (not the sunniest of countries) it is widely used in Mediterranean countries and there has been a phenomenal growth in its use in recent years in China.

Section 2.3 described the nature of solar radiation starting with the important distinction between 'light' (i.e. short-wave radiation) and 'heat' (long-wave radiation). Direct radiation, the unobstructed rays of the Sun, is important for concentrating collectors, and diffuse radiation is important for natural lighting. The total amount of solar radiation available over a year varies from country to country and is higher in those at a lower latitude (i.e. closer to the equator). Optimizing the amount of radiation falling on a flat plate collector requires an understanding of the appropriate tilt, which will depend on the latitude of the site.

Section 2.4 turned to the properties of glass and other plastic glazing materials, particularly their ability to transmit light but block the re-radiation of long-wave infrared radiation (heat). It described the three mechanisms of heat loss: conduction, convection and radiation in the context of a double glazed window. It introduced the *U*-value as a measure of heat loss and described ways in which window *U*-values could be reduced.

Section 2.5 described some possible low-temperature applications for solar energy, particularly domestic solar water heating and space heating. It pointed out that the need for winter space heating is highly dependent on the local climate. It also introduced the 'heat pump', which although not directly a 'solar' technology, does draw heat from the outside environment and is a rival for the production of low-temperature heat. The section ended with a brief description of three 'passive solar' technologies where the solar collector is an integral part of a building: the conservatory, the Trombe wall and direct gain collection.

Section 2.6 looked at 'active solar heating' in more detail, describing four basic collector types and their applications.

Section 2.7 described the complex topic of passive solar heating in detail, particularly 'direct gain' design, looking at a south-facing window as a solar collector and the actual heating energy needs of house. These in turn relate to its insulation level and the role of 'free heat gains' from people, lights and appliances. It discussed the choice between 'solar' and 'superinsulated' design, the latter being recently expressed in the form of *Passivhaus* projects. It briefly described other passive solar technologies: conservatories, greenhouses and atria, and the use of sunpath diagrams as a tool for avoiding overshading.

Section 2.8 briefly described the use of daylighting in avoiding excessive use of artificial light.

Section 2.9 turned to the use of solar thermal energy to drive engines and particularly to generate electricity, in what is now known as concentrating solar power (CSP). It described the basic forms of concentrating collector: the line focus or parabolic trough, and the point focus or dish collector. These were used in large CSP plants in California in the 1980s and there has been a resurgence of construction since 2005. It also introduced the 'power tower' design, where steerable flat mirrors or *heliostats* are used to concentrate the Sun's rays on a central receiver. These form the basis of new CSP plants constructed in Spain. Box 2.4 described the importance of achieving high temperatures in order to get a high overall engine efficiency. It also introduced the organic Rankine cycle (ORC) used in other low-temperature systems, and also briefly described solar ponds, ocean thermal energy conversion (OTEC) and solar updraft towers.

Finally Section 2.10 looked at the economics, potential and environmental impact of solar thermal systems. Although heat pumps may be more economic in the UK, solar water heating is highly viable in central and southern Europe. Mass manufacturing of solar water heaters in China has led to low collector costs and been responsible for the extraordinary growth in collector sales there over the past decade. The economics of concentrating solar power is sufficiently good to support proposals for several gigawatts of new construction in the USA alone.

Globally, the future outlook for solar heating and concentrating solar power generation looks very good. Other 'solar' technologies such as heat pumps and *Passivhaus* energy conservation technology offer considerable potential for reducing global CO_2 emissions.