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.

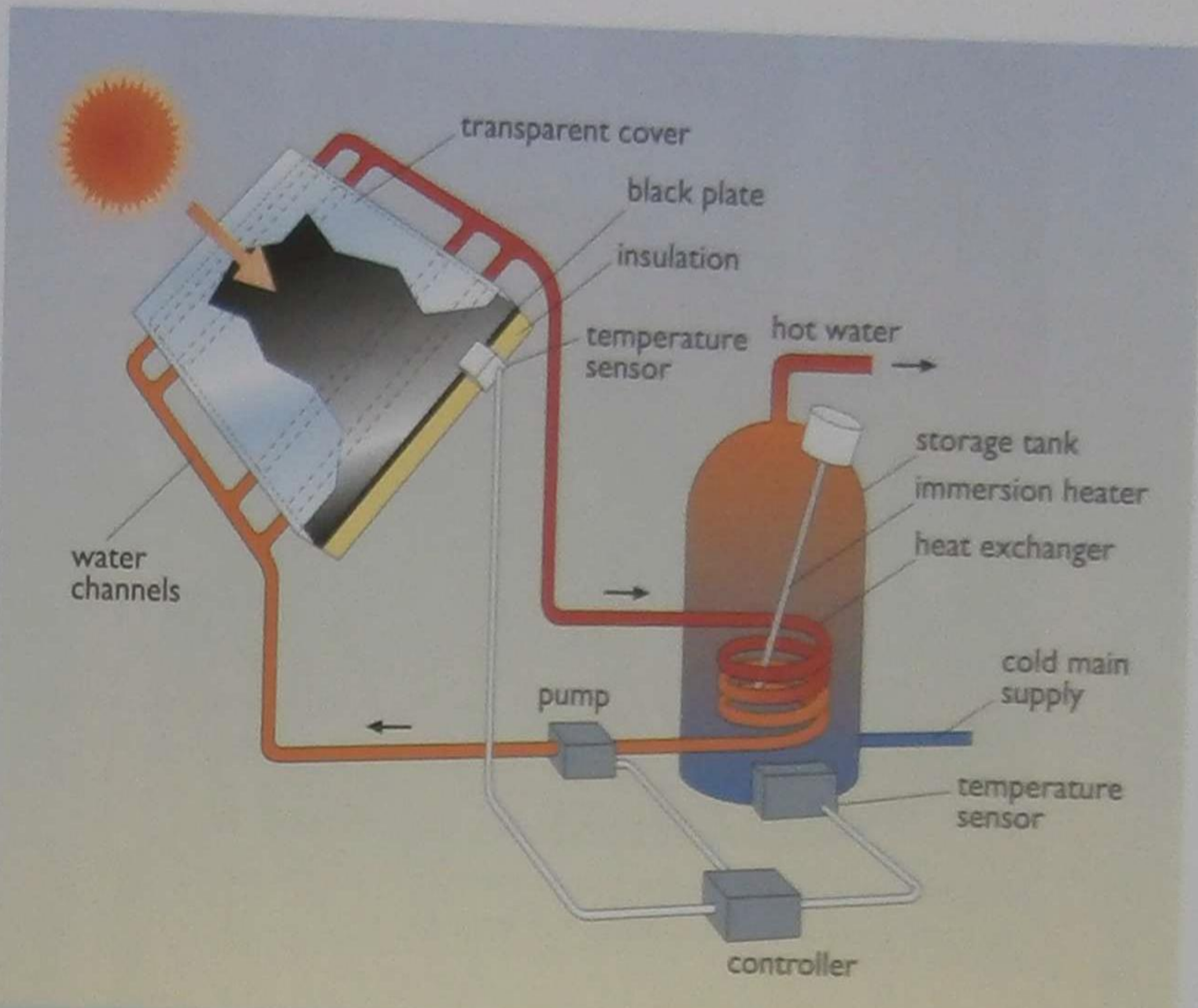


Figure 2.2 Pumped active solar water heater

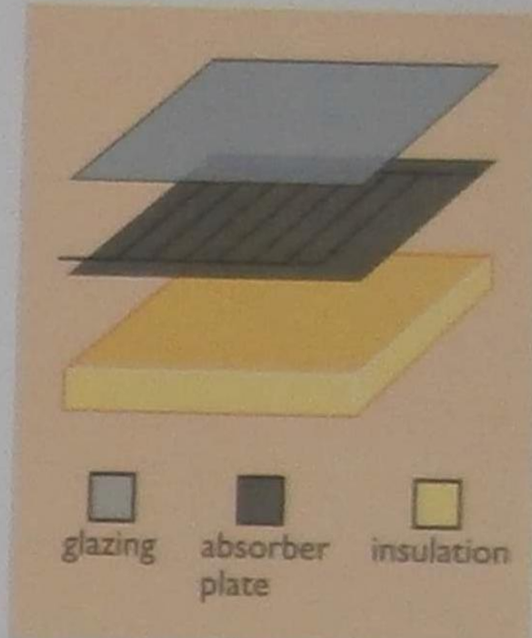
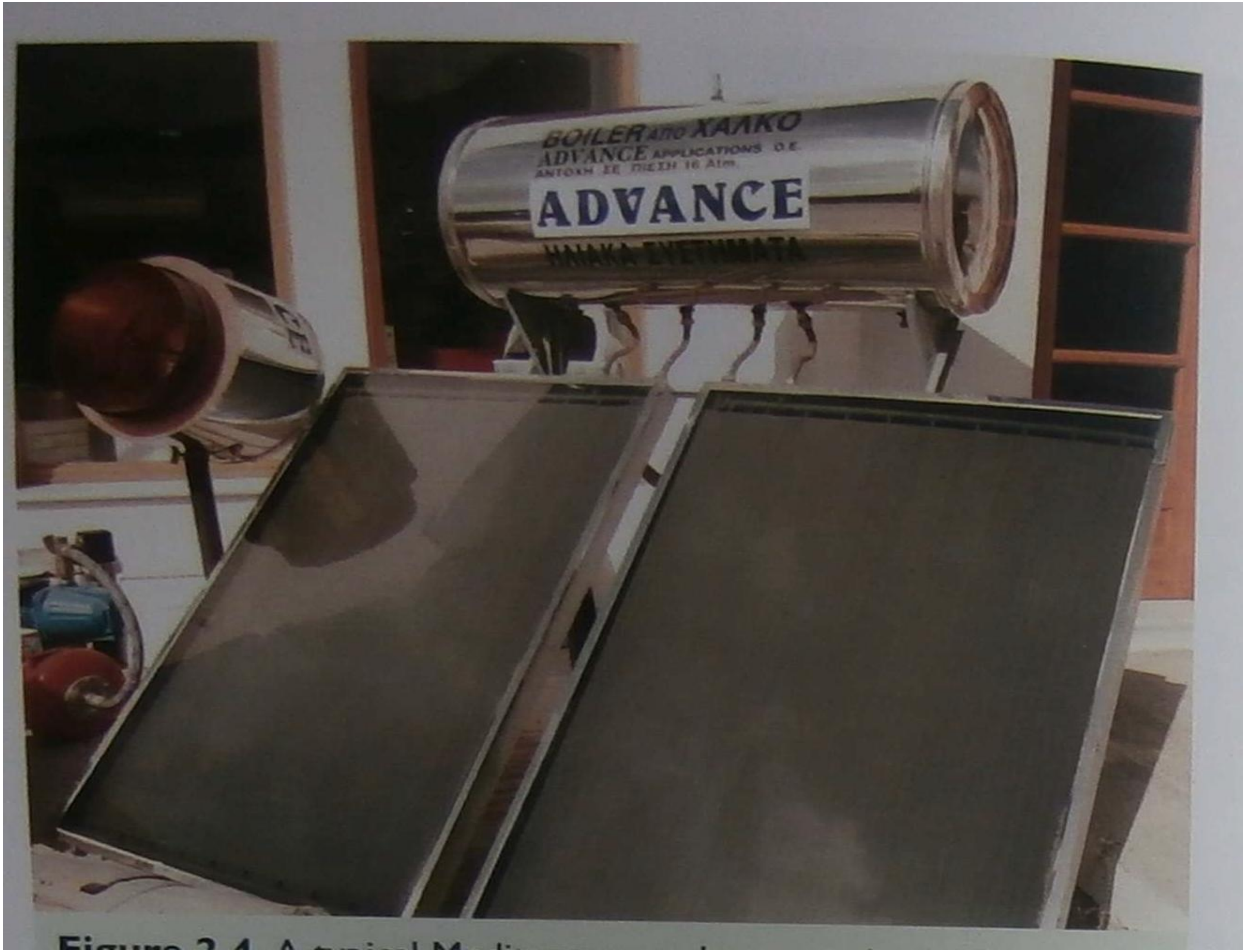


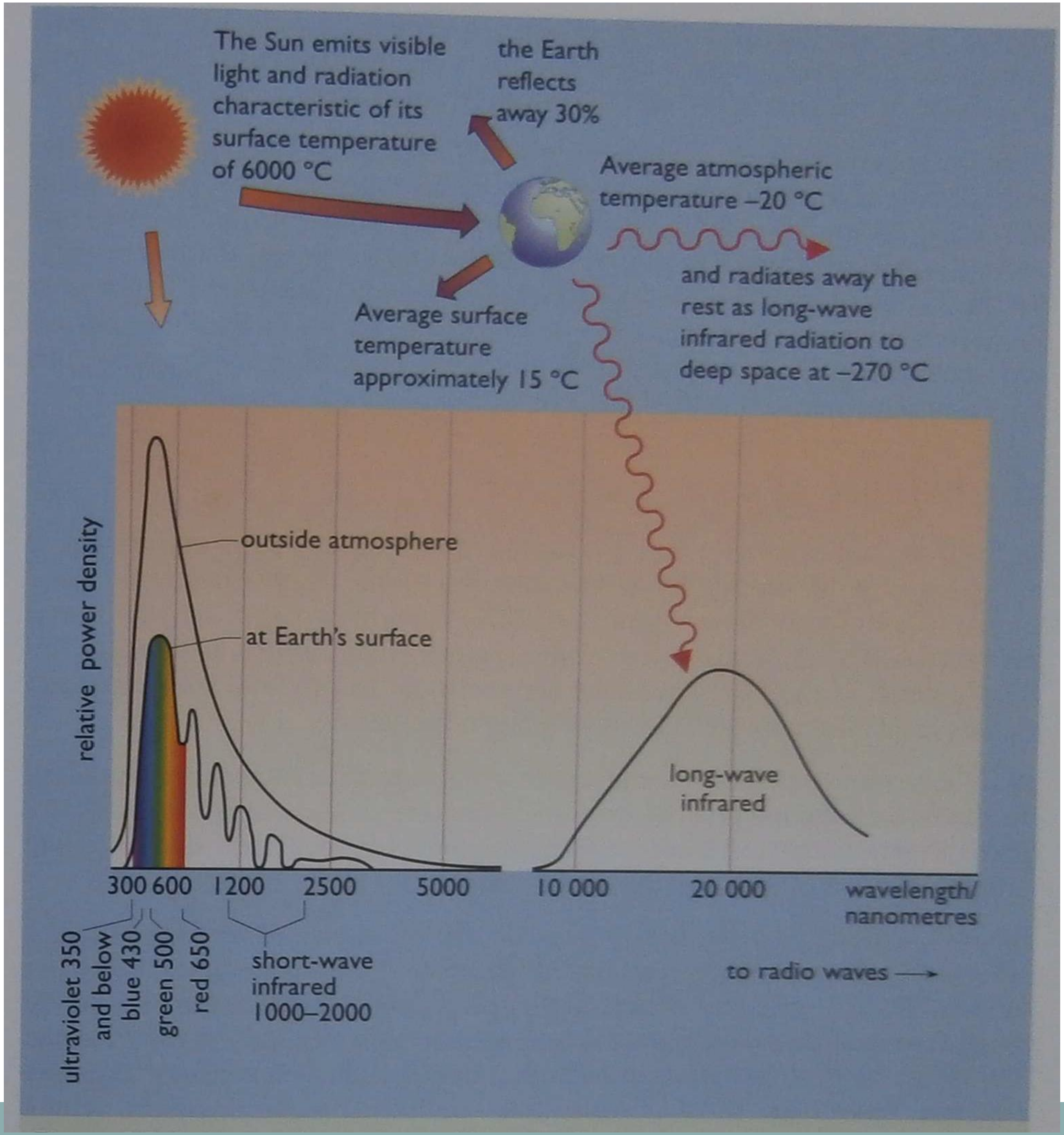
Figure 2.3 Components of a solar panel

(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.

(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).


BOILER απο ΧΑΛΚΟ
ADVANCE APPLICATIONS O.E.
ΑΝΤΟΧΗ ΣΕ ΠΙΕΣΗ 16 Atm
ADVANCE



The Sun emits visible light and radiation characteristic of its surface temperature of 6000 °C
the Earth reflects away 30%
Average atmospheric temperature –20 °C
and radiates away the rest as long-wave infrared radiation to deep space at –270 °C
Average surface temperature approximately 15 °C
relative power density
outside atmosphere
at Earth's surface
long-wave infrared
300 600 1200 2500 5000 10 000 20 000
wavelength/ nanometres
ultraviolet 350 and below
blue 430
green 500
red 650
short-wave infrared 1000–2000
to radio waves →

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}.

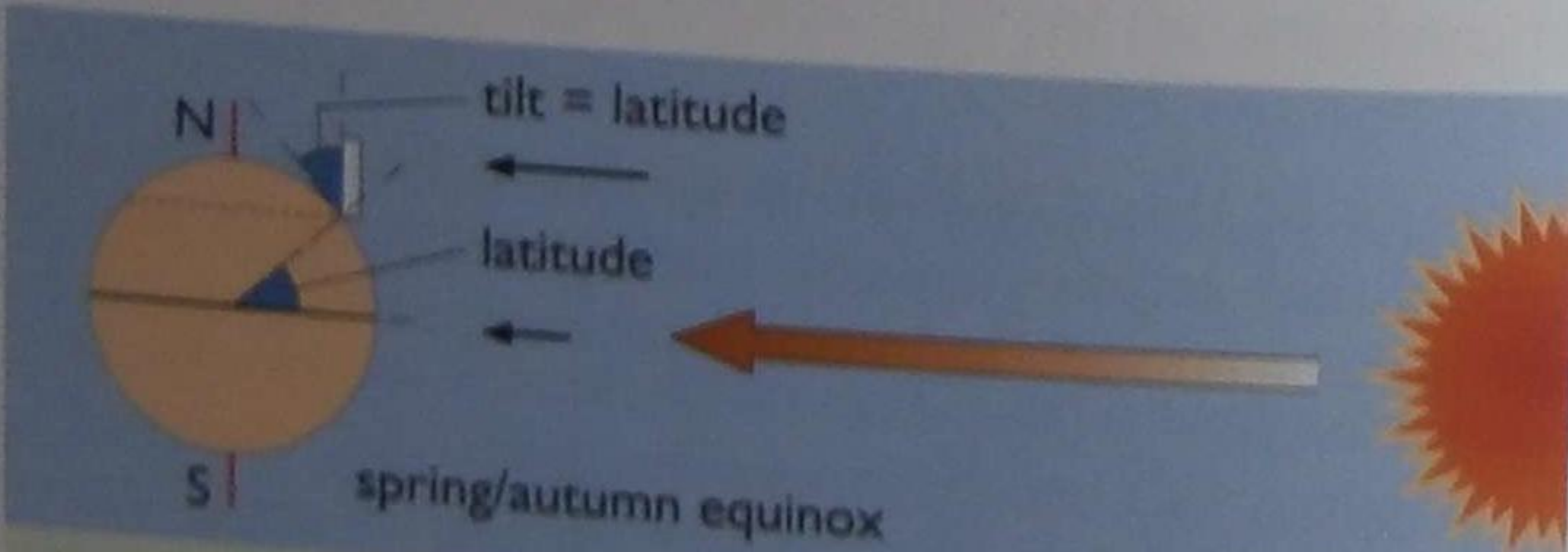


Figure 2.9 A surface tilted at the latitude angle will be perpendicular to the Sun's rays at mid-day on the spring or autumn equinox

re is also the differ

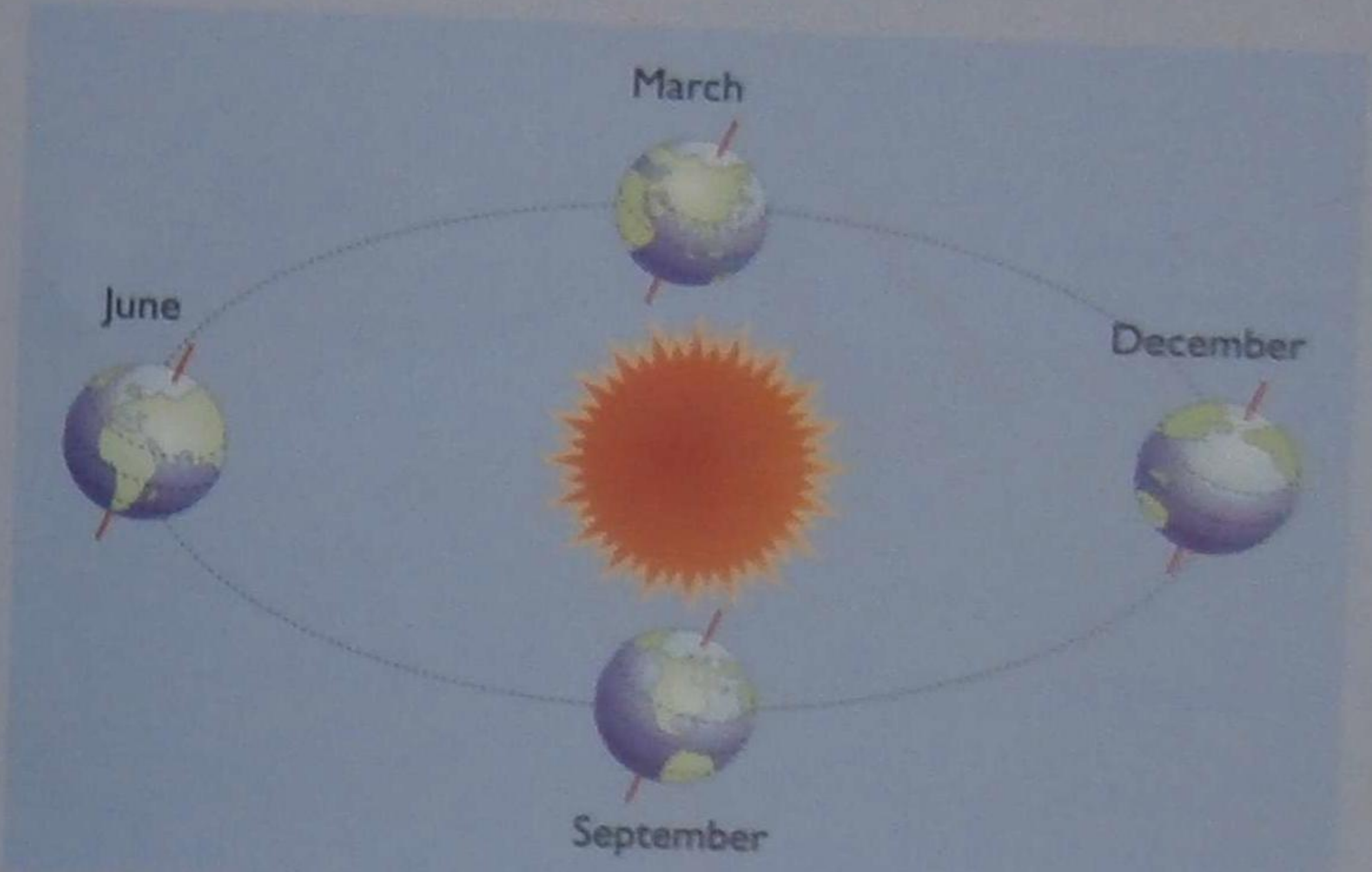


Figure 2.10 The Earth revolves around the Sun with its axis tilted at an angle of 23.5° to the plane of rotation

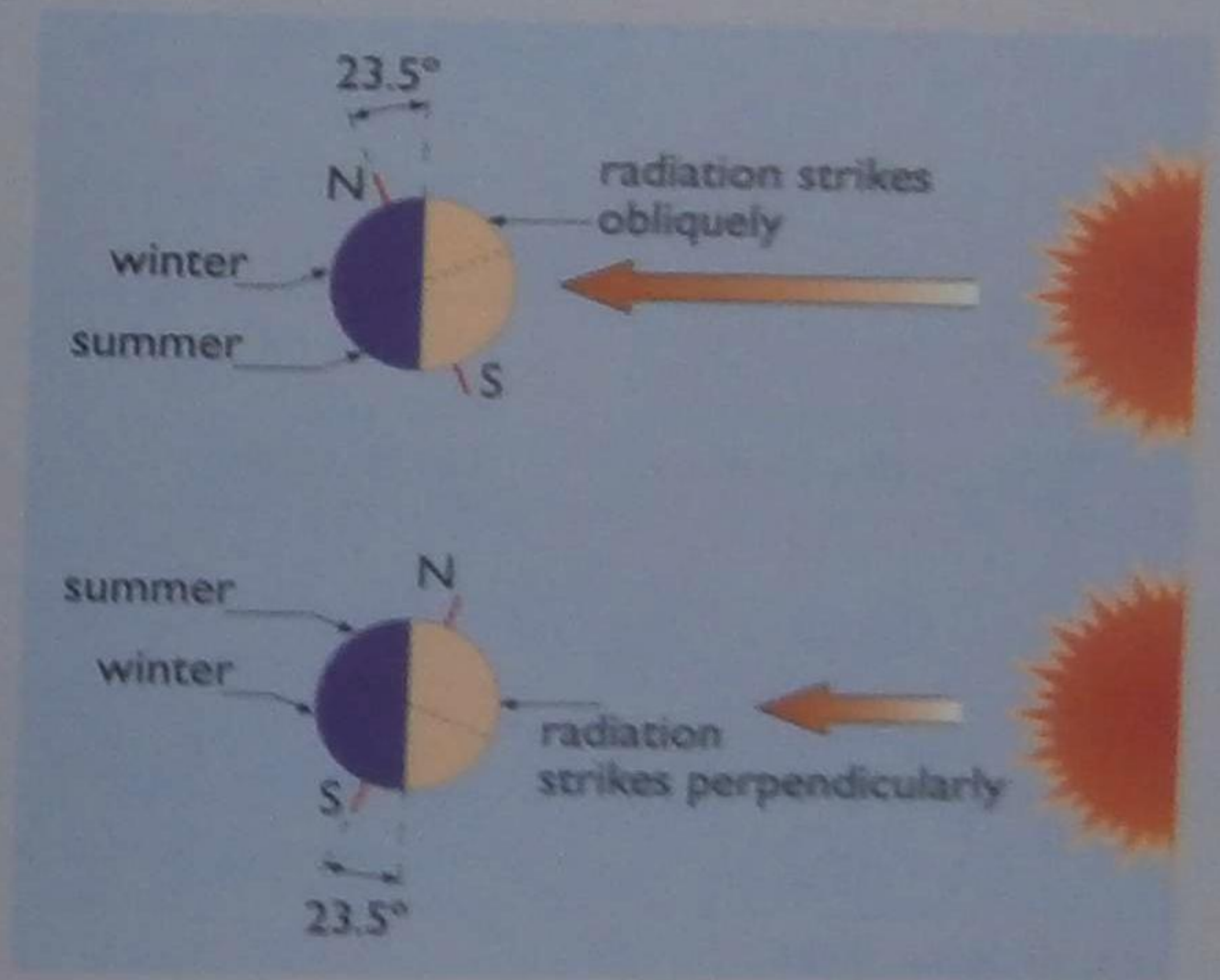


Figure 2.11 The tilt of the Earth's axis creates summer and winter

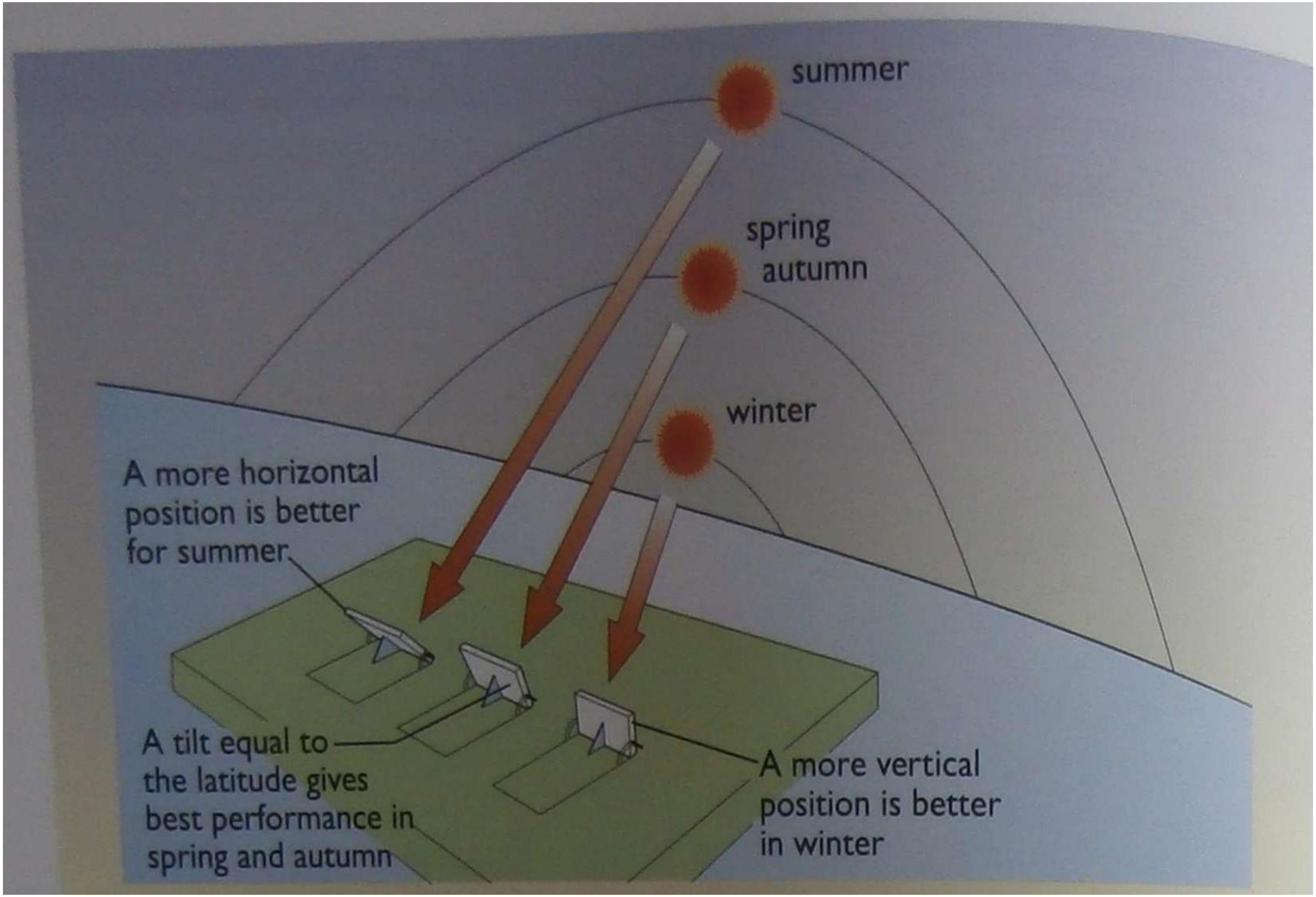

summer
spring
autumn
winter
A more horizontal position is better for summer
A tilt equal to the latitude gives best performance in spring and autumn
A more vertical position is better in winter

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

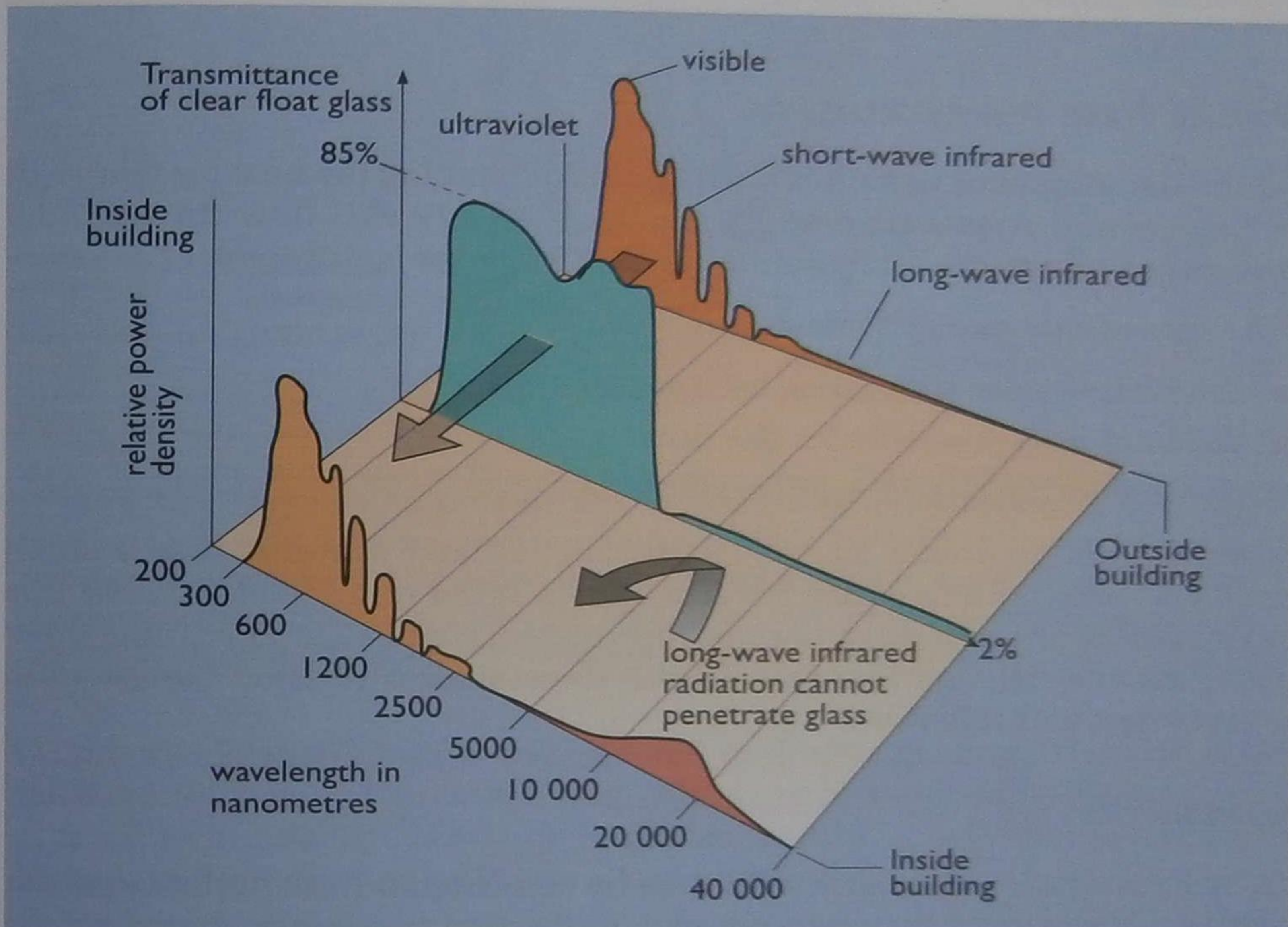


Figure 2.13 Spectral transmittance of glass

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.

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 $W\ m^{-2}\ {}^{\circ}C^{-1}$.

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

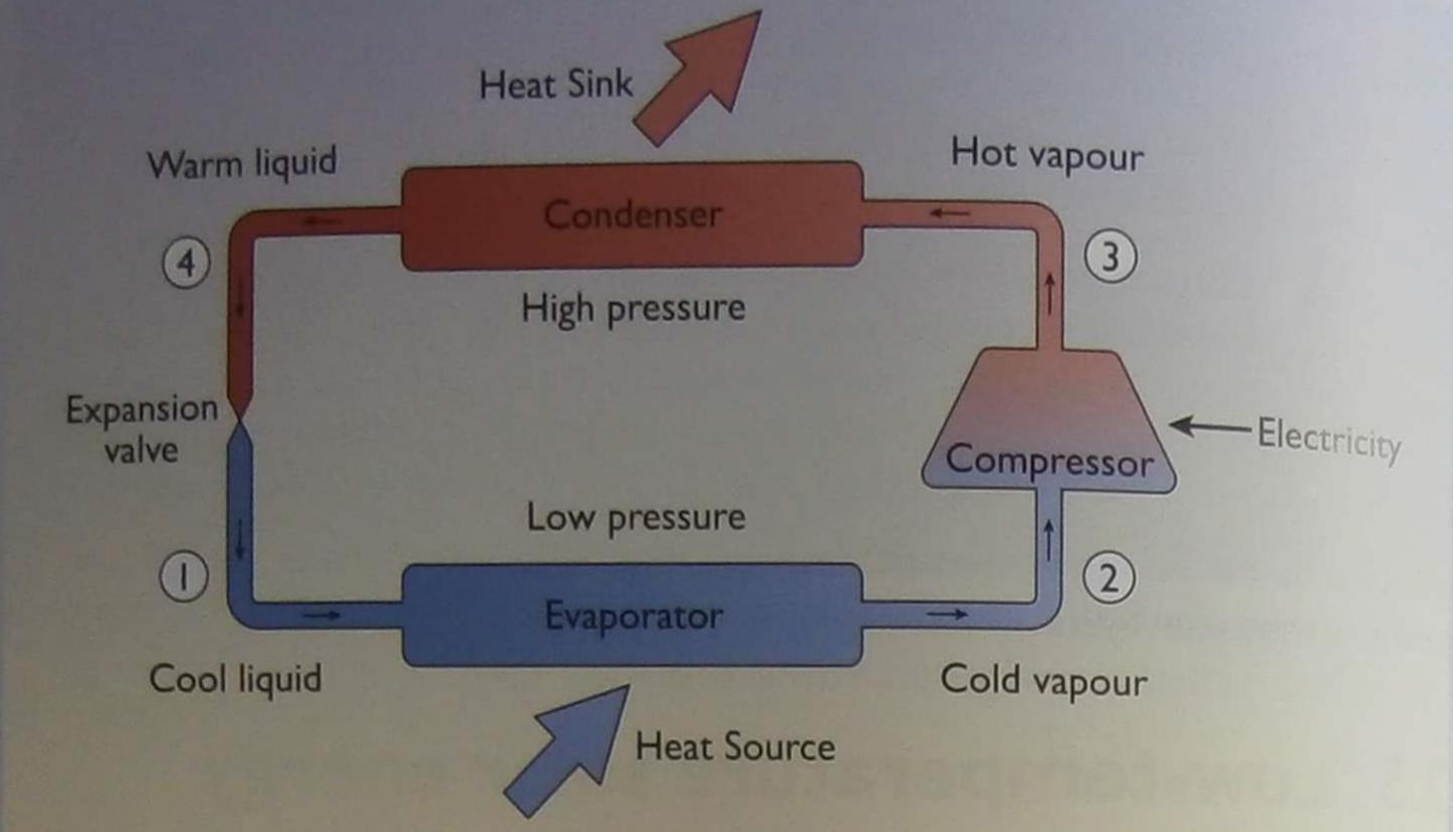


Figure 2.16 Schematic diagram of a heat pump (source: EST, 2010)

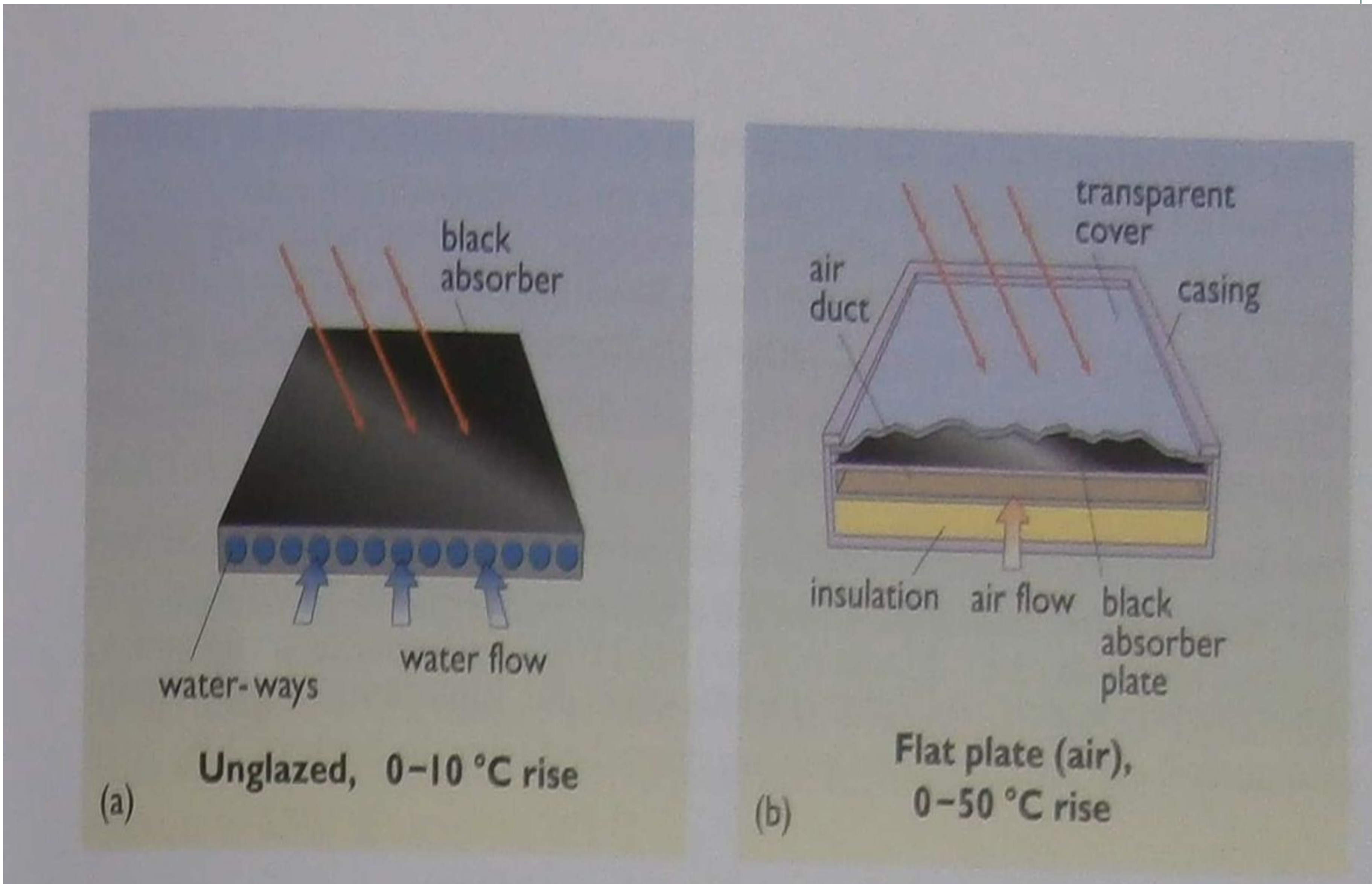
Domestic water heating

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.


black
absorber
water-ways
water flow
Unglazed, 0–10 °C rise
(a)
transparent
cover
air
duct
casing
insulation
air flow
black
absorber
plate
Flat plate (air),
0–50 °C rise
(b)

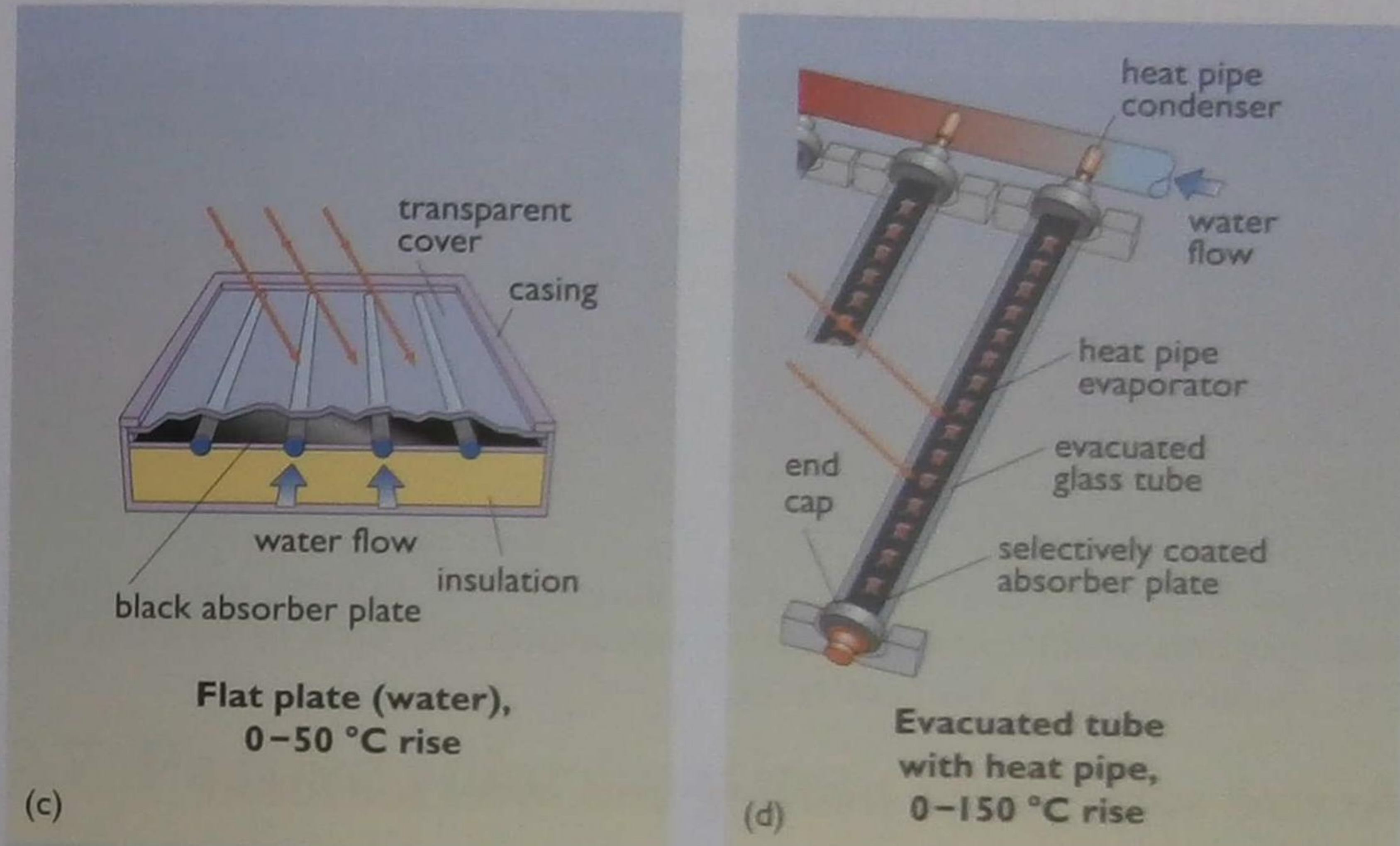


Figure 2.23 Solar collectors for low-temperature collection

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

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.

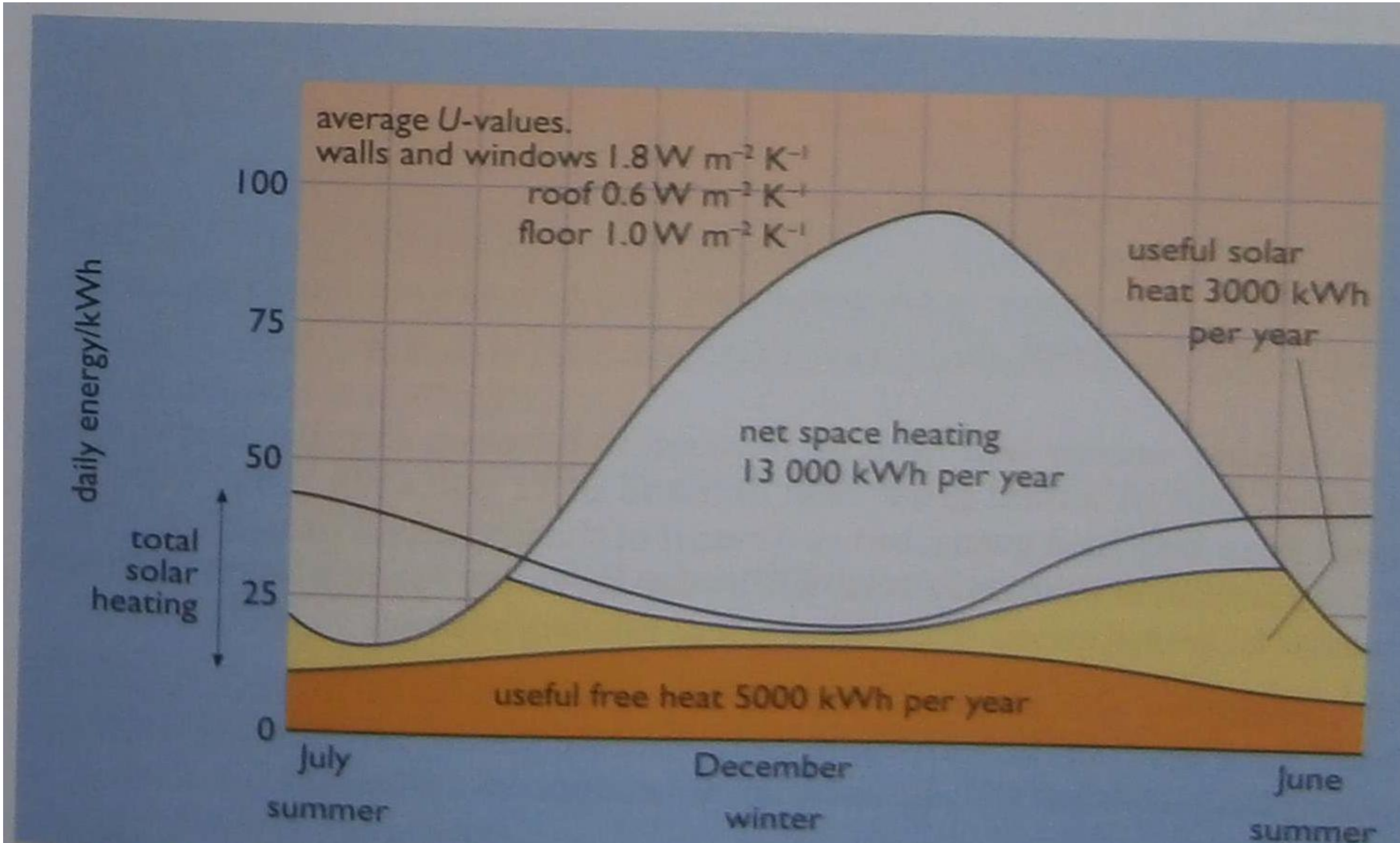


Figure 2.29 Contribution to the net space heating demand in a typical poorly insulated UK house of the 1970s

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.

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 guidelin

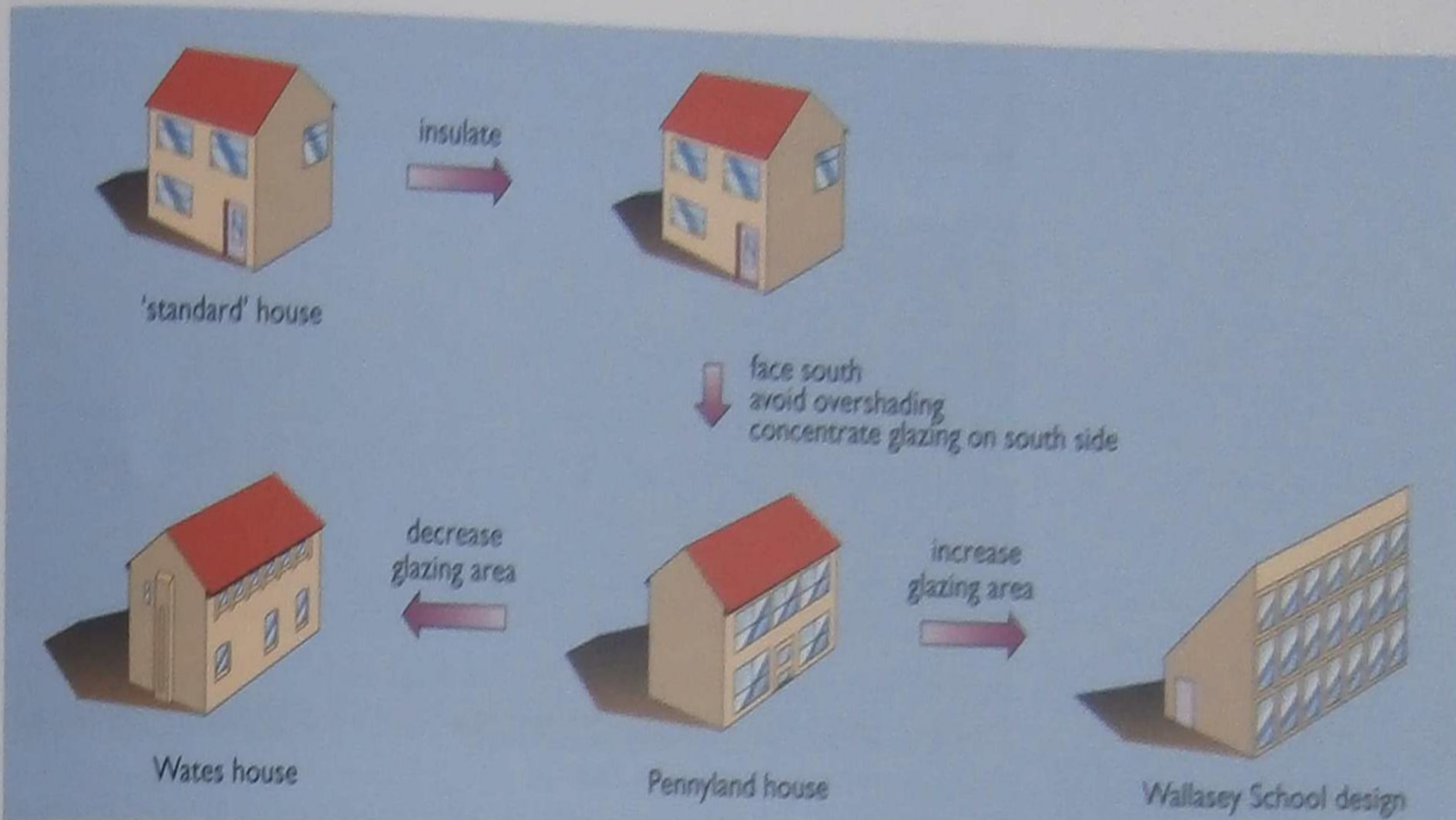


Figure 2.33 Design steps in low-energy housing

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

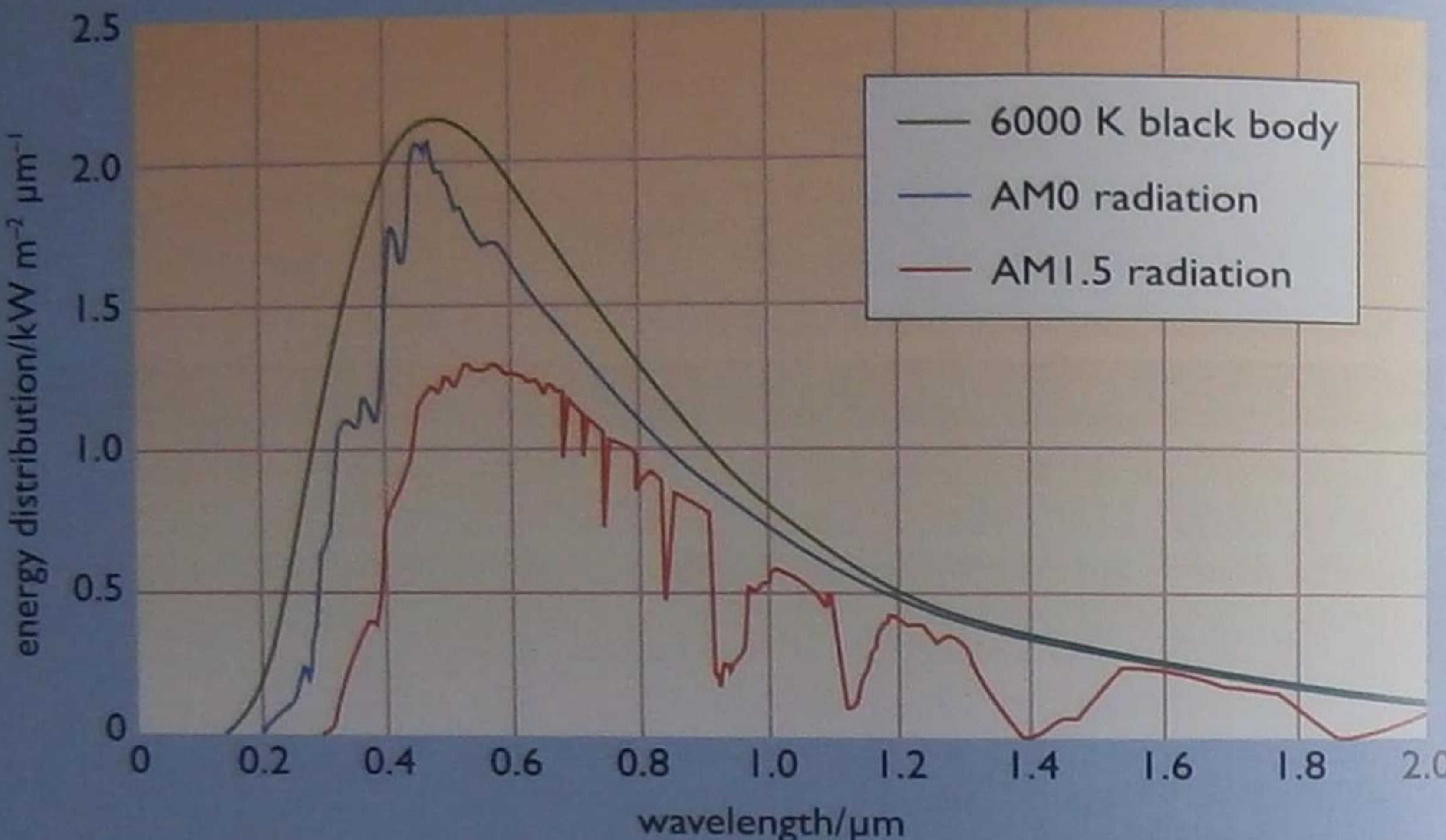
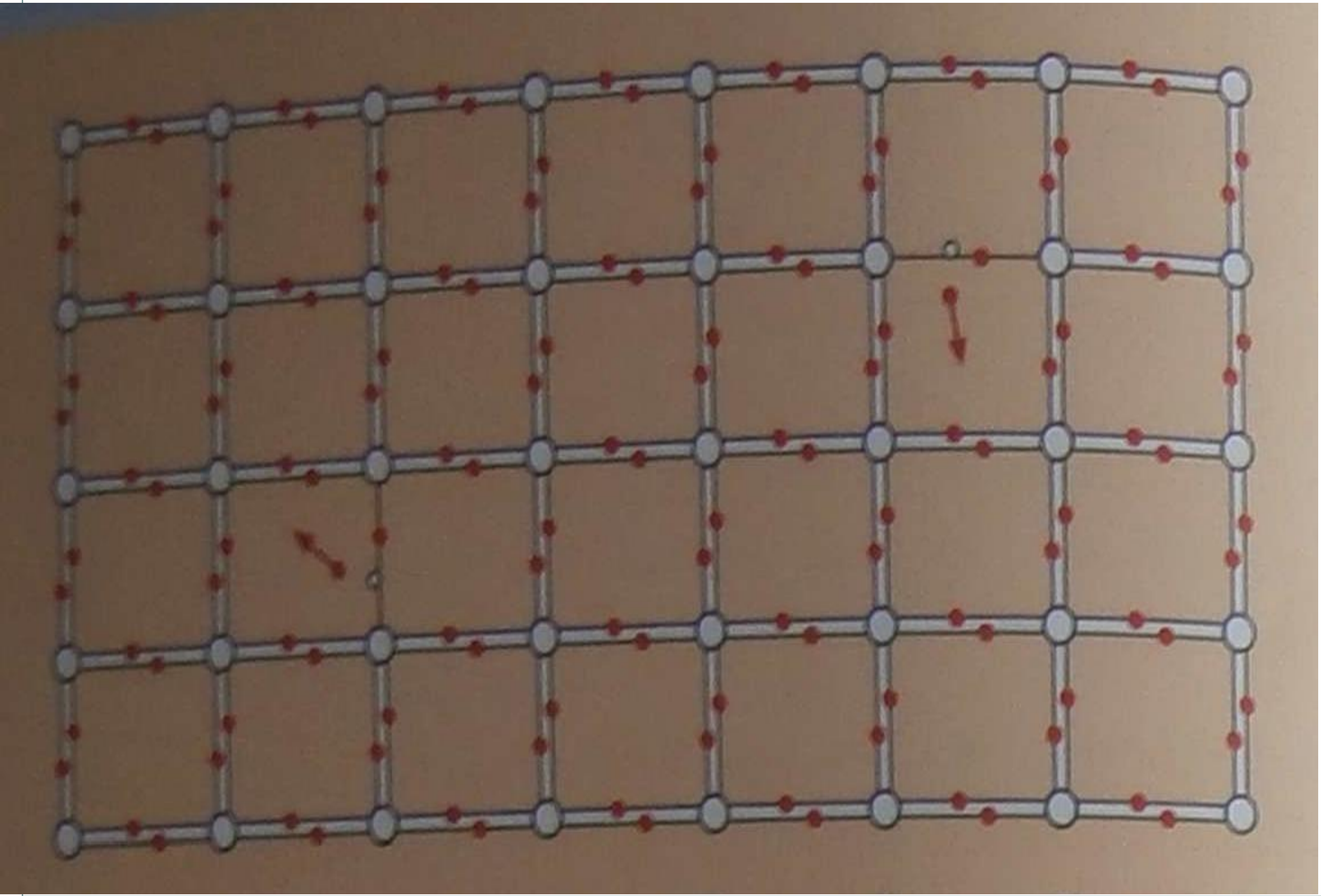
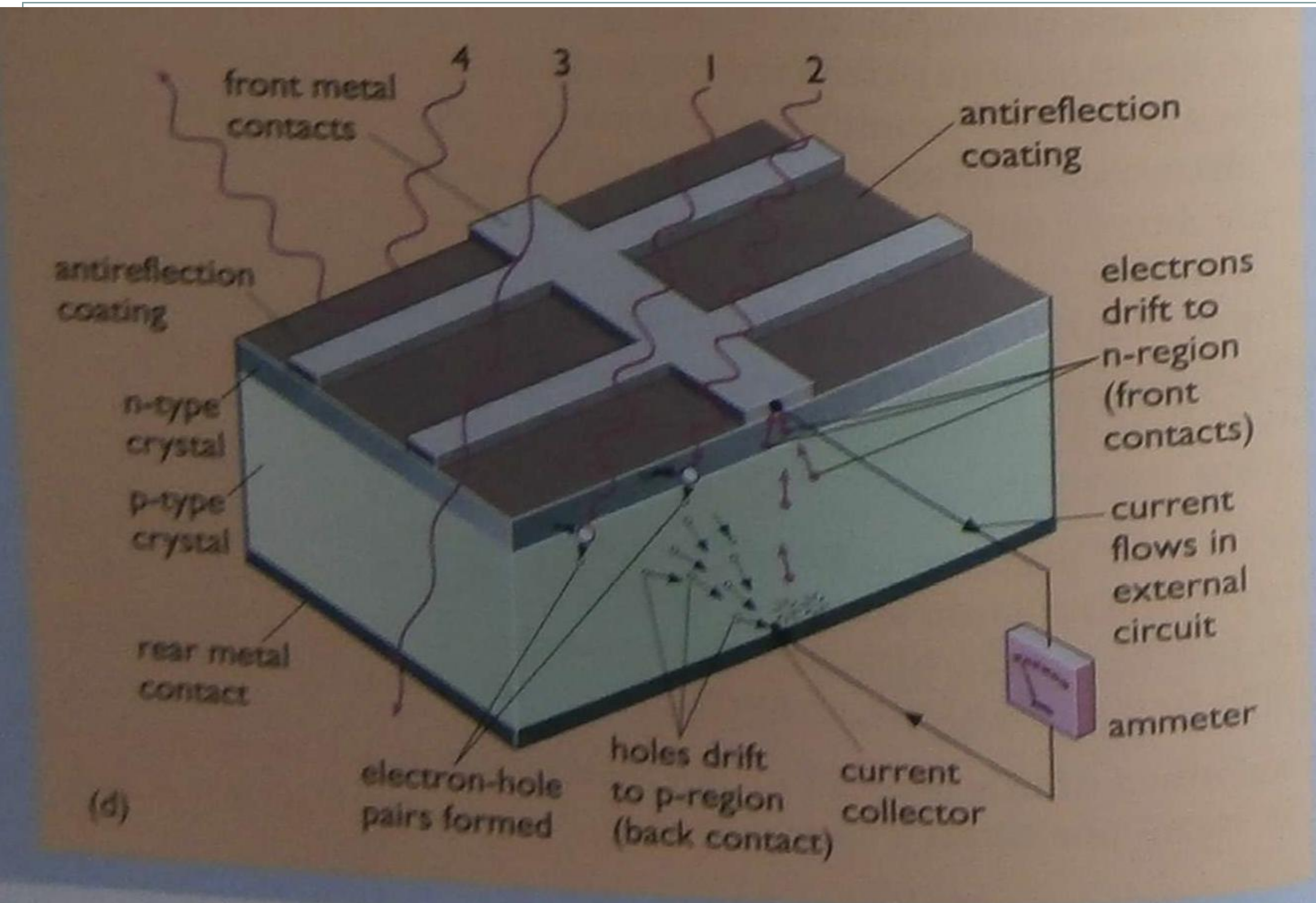


Figure 3.9 The spectral power distributions of solar radiation corresponding to Air Mass 0 and Air Mass 1.5. Also shown is the theoretical spectral power distribution which would be expected, in space, if the Sun were a perfect radiator (a 'black body') at 6000 °C

Light can be considered to consist of a stream of tiny particles of energy, called **photons**. When photons from light of a suitable wavelength fall within the p–n junction, they can transfer their energy to some of the electrons in the material, so 'promoting' them to a higher energy level. Normally, these electrons help to hold the material together by forming so-called 'valence' bonds with adjoining atoms, and cannot move. In their 'excited' state, however, the electrons become free to conduct electric current by moving through the material. In addition, when electrons move they leave behind holes in the material, and these can also move (Box 3.2). The 'car parking' analogy shown in Figure 3.10 may be helpful in visualizing the processes involved.

When the p–n junction is formed, some of the electrons in the immediate vicinity of the junction are attracted from the n-side to combine with holes on the nearby p-side. Similarly, holes on the p-side near the junction are attracted to combine with electrons on the nearby n-side.





4
3
1
2
front metal contacts
antireflection coating
antireflection coating
electrons drift to n-region (front contacts)
n-type crystal
p-type crystal
current flows in external circuit
rear metal contact
ammeter
electron-hole pairs formed
holes drift to p-region (back contact)
current collector
(d)

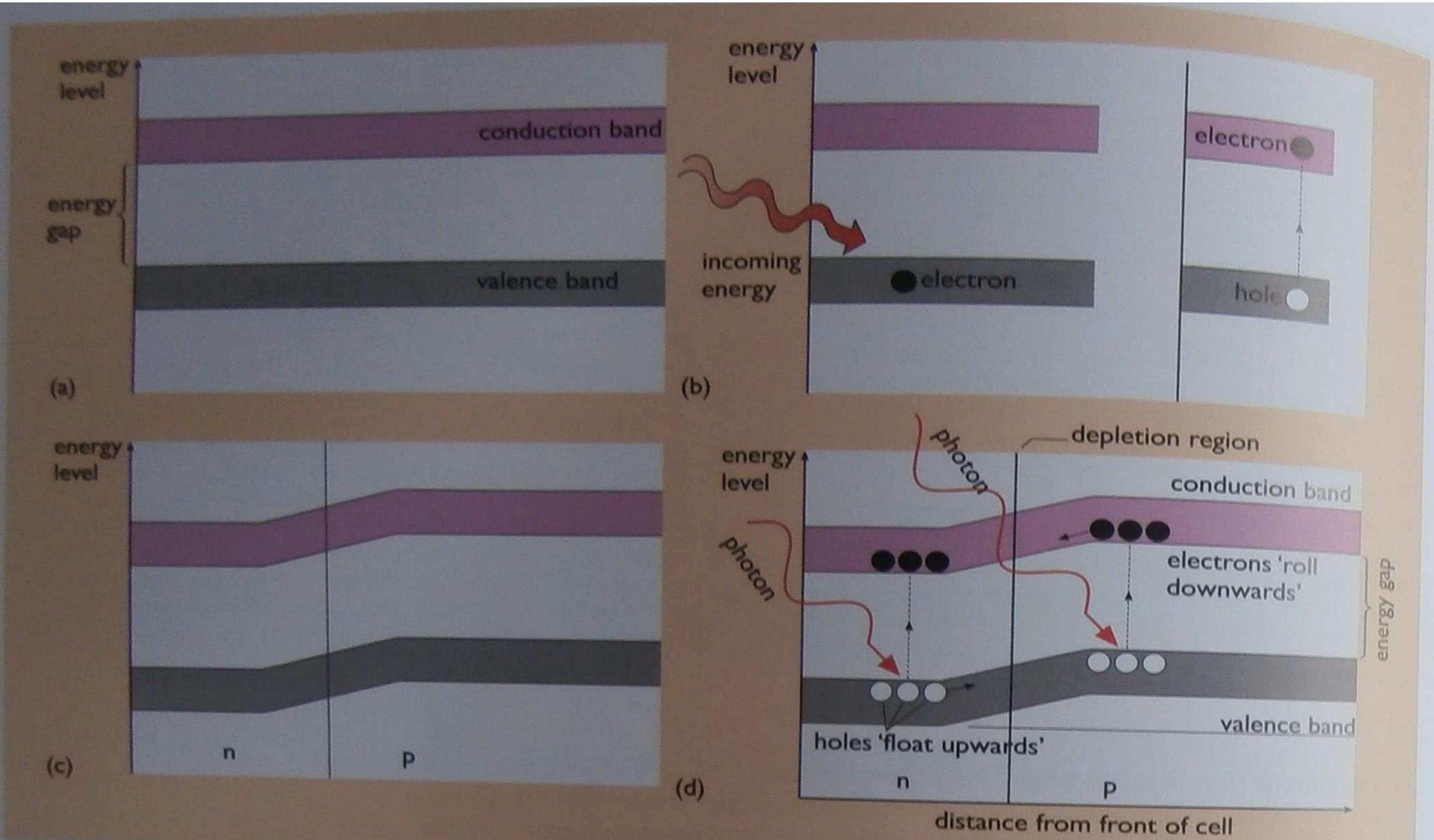


Figure 3.12 (a) Energy bands in a normal ('intrinsic') semiconductor (b) An electron can be 'promoted' to the conduction band when it absorbs energy from light (or heat), leaving behind a 'hole' in the valence band (c) When n-type and p-type semiconductors are combined into a p–n junction, their different energy bands combine to give a new distribution, as shown, and a built-in electric field is created (d) In the p–n junction, photons of light can excite electrons from the valence band to the conduction band. The electrons 'roll downwards' to the n-region, and the holes 'float upwards' to the p-region

One very simple way of envisaging a typical silicon PV cell is as a solar-powered battery that produces a voltage of around 0.5 V and delivers a current, proportional to cell size and sunlight intensity, of several amps.

In order to use PV cells efficiently we need to know a little more about how they behave when connected to electrical loads. Figure 3.20 shows a single silicon PV cell connected to a variable electrical resistance R, together with an ammeter to measure the current (I) flowing in the circuit and a voltmeter to measure the voltage (V) developed across the cell terminals. Let us assume the cell is being tested under standard conditions (see Box 3.1).

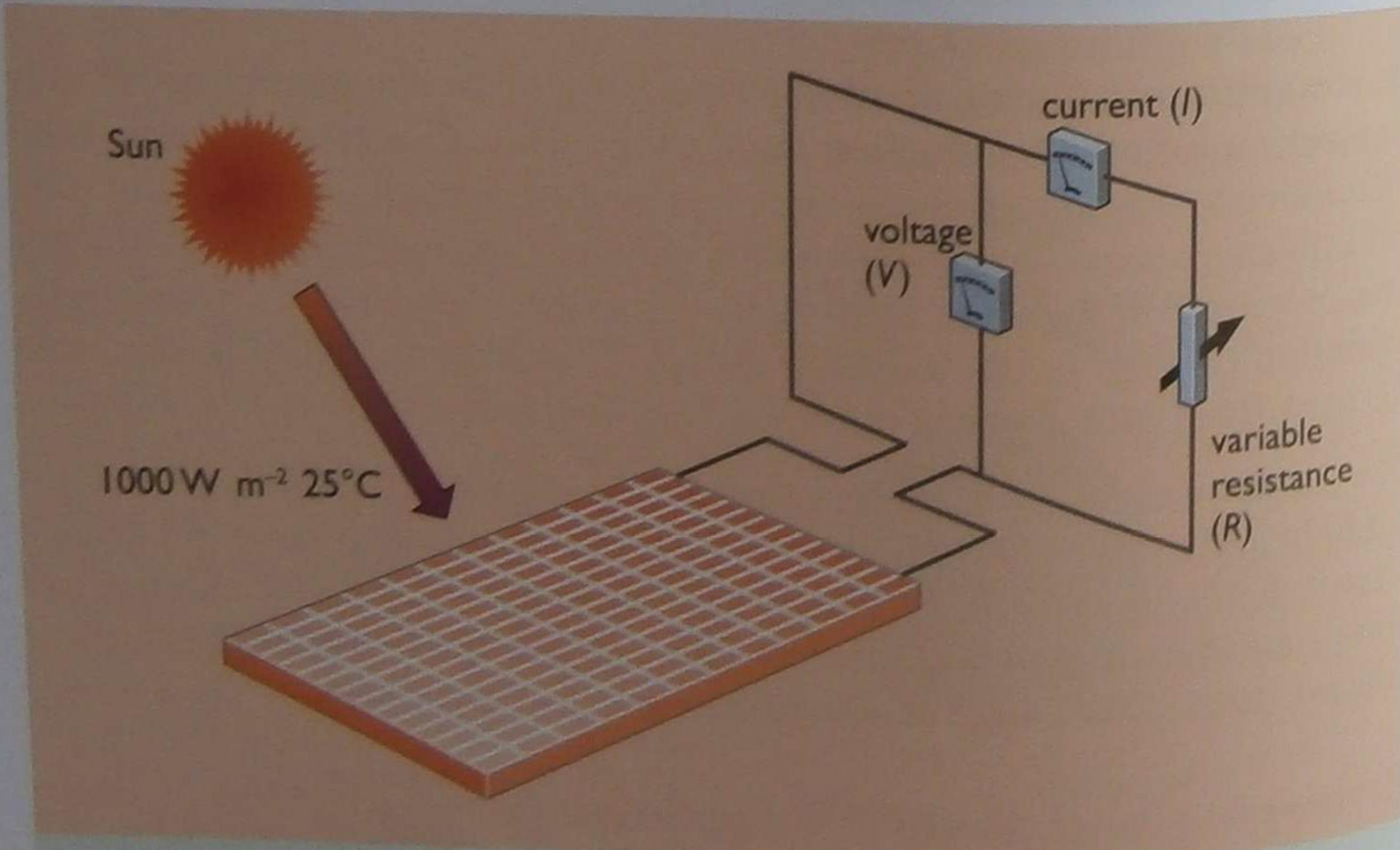


Figure 3.20 PV cell connected to variable resistance, with ammeter and voltmeter to measure variations in current and voltage as resistance varies

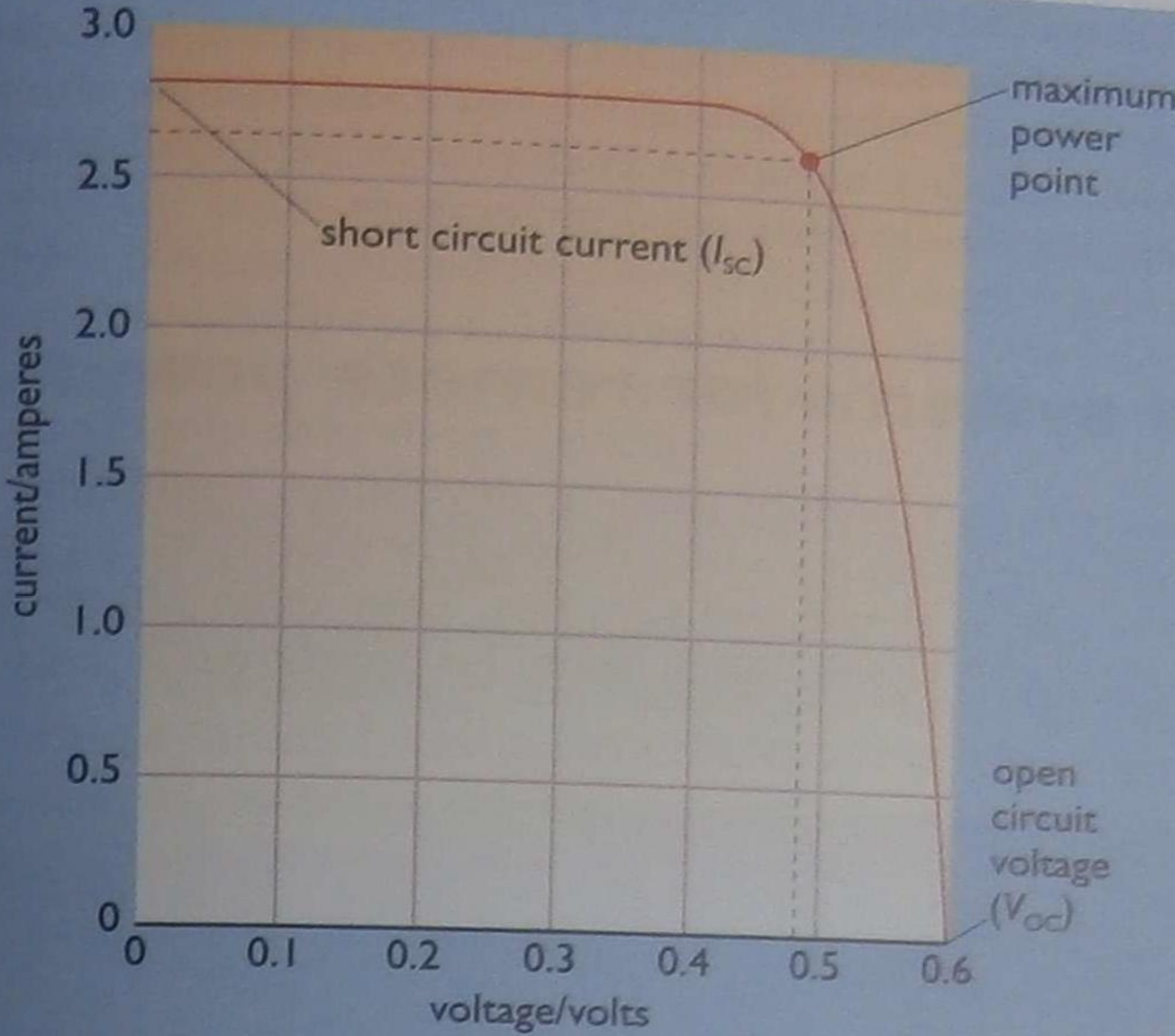


Figure 3.21 Current–voltage (I–V) characteristics of a typical silicon PV cell under standard test conditions

When the resistance is infinite (i.e. when the cell is 'open circuited') the current in the circuit is at its minimum (zero) and the voltage across the cell is at its maximum, known as the **'open circuit voltage'** (V_{OC}). At the other extreme, when the resistance is zero, the cell is in effect 'short circuited' and the current in the circuit then reaches its maximum, known as the **'short circuit current'** (I_{SC}).

If we vary the resistance between zero and infinity, the current (I) and voltage (V) will be found to vary as shown in Figure 3.21, which is known as the 'I–V characteristic' or 'I–V curve' of the cell. It can be seen from the graph that the cell will deliver maximum power (i.e. the maximum product of voltage and current) when the external resistance is adjusted so that its value corresponds to the **maximum power point** (MPP) on the I–V curve.