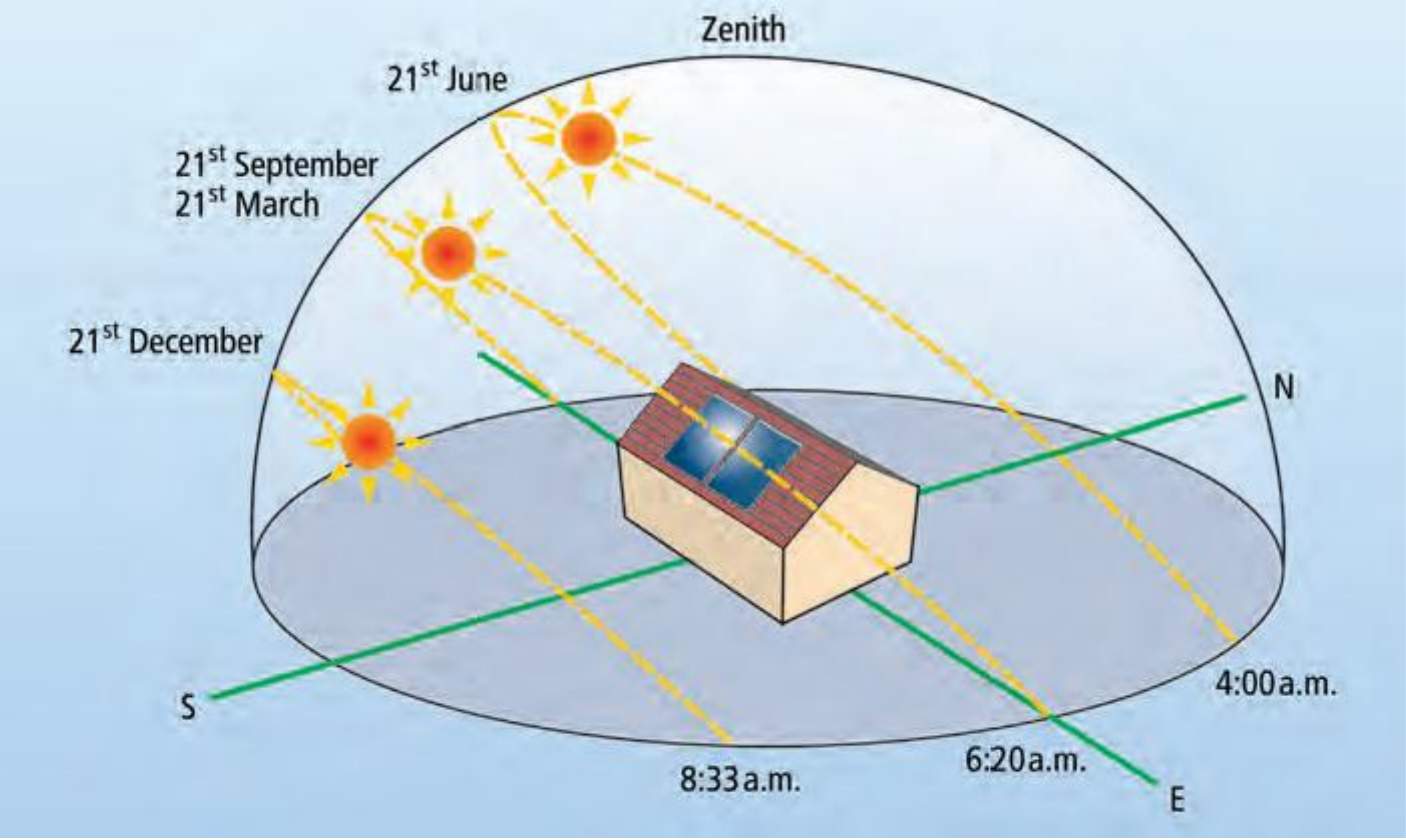
1.1.1 Solar energy

The most important supplier of energy for the earth is the *sun*. The whole of life depends on the sun’s energy. It is the starting point for the chemical and biological processes on our planet. At the same time it is the most environmentally friendly form of all energies, it can be used in many ways, and it is suitable for all social systems.

In the core of the sun a fusion process takes place in which pairs of hydrogen nuclei are fused into helium nuclei. The energy thus released is radiated into space in the form of electromagnetic radiation. As the sun is 148 million km from the earth, it radiates only a tiny fraction of its energy to the earth. In spite of this, *the sun offers more energy in four hours than the human race uses in a whole year*.


Zenith
21st June
21st September
21st March
21st December
N
S
E
4:00 a.m.
6:20 a.m.
8:33 a.m.

IRRADIATED POWER, IRRADIANCE, HEAT QUANTITY

When we say that the sun has an irradiance, G, of for example 1000 W/m2, what is meant here is the capability of radiating a given irradiated power, ϕ (1000 W), onto a receiving surface of 1 m2 (10.76 ft2).

The watt is the unit in which power can be measured. If this power is referred, as in this case, to a unit area, then it is called the irradiance.

1 kW (kilowatt) = 103 W (1000 watts)
1 MW (megawatt) = 106 W (1 million watts) = 103 kW
1 GW (gigawatt) = 109 W (1 thousand million watts) = 106 kW
1 TW (terawatt) = 1012 W (1 million million watts) = 109 kW

When the sun shines with this power of 1000 W for 1 hour it has performed 1 kilowatt-hour of work (1 kWh) (Work = Power × Time).
If this energy were converted completely into heat, a heat quantity of 1 kWh would be produced.
Irradiated power, ϕ (W)
Irradiance, G (W/m2)
Heat quantity, Q (Wh, kWh)

other directions and not just directly from the sun. This proportion of the radiation, which reaches the eye of the observer through the scattering of air molecules and dust particles, is known as *diffuse radiation*, $G\mathrm{dif}$. Part of this is also due to radiation reflected at the earth’s surface. The radiation from the sun that meets the earth without any change in direction is called *direct radiation*, $G\mathrm{dir}$. The sum of direct and diffuse radiation is known as *global solar irradiance*, $G\mathrm{G}$ (Figure 1.5).

$$G\mathrm{G} = G\mathrm{dir} + G\mathrm{dif}$$

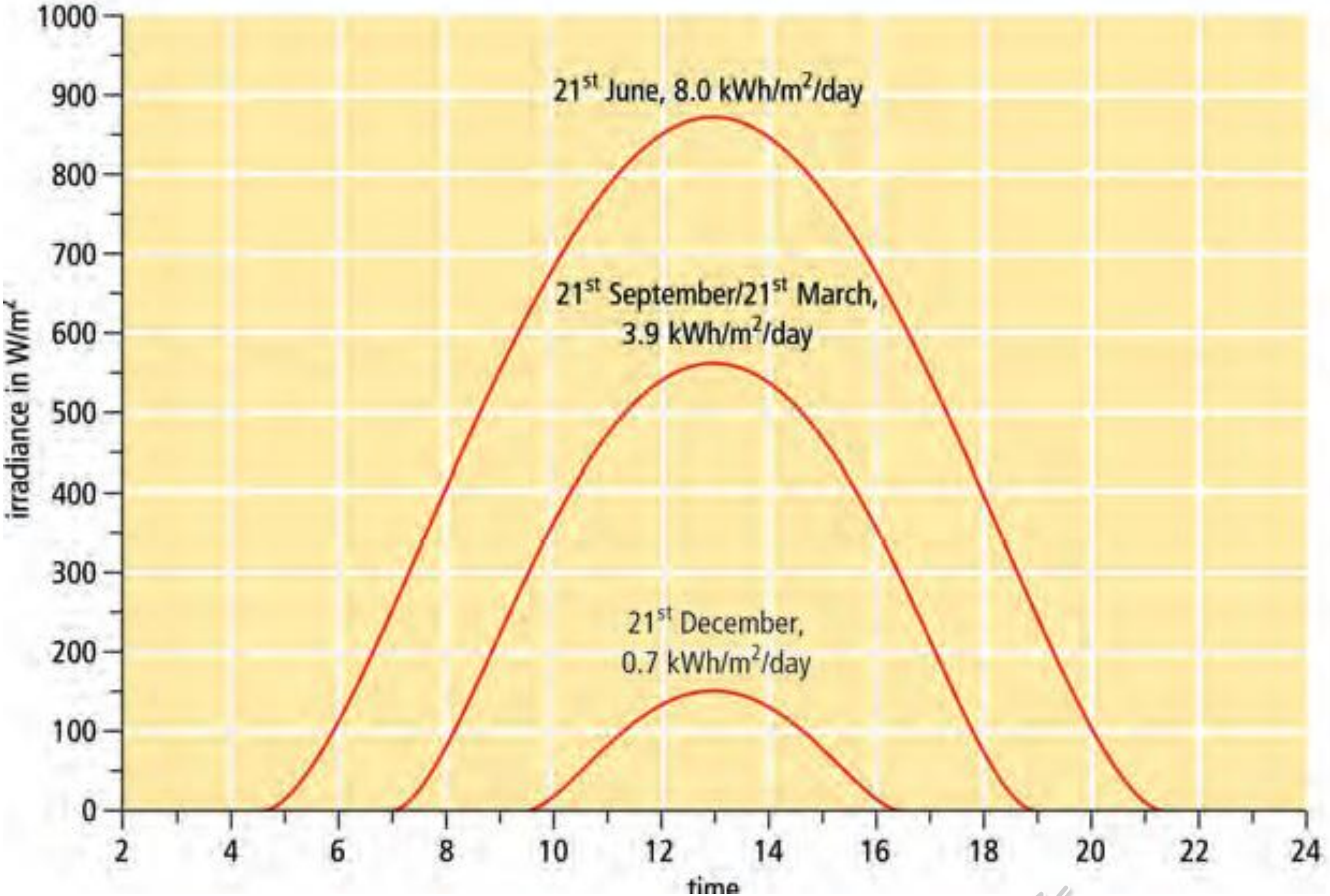


Figure 1.3.
Daily courses and daily totals for irradiation in London

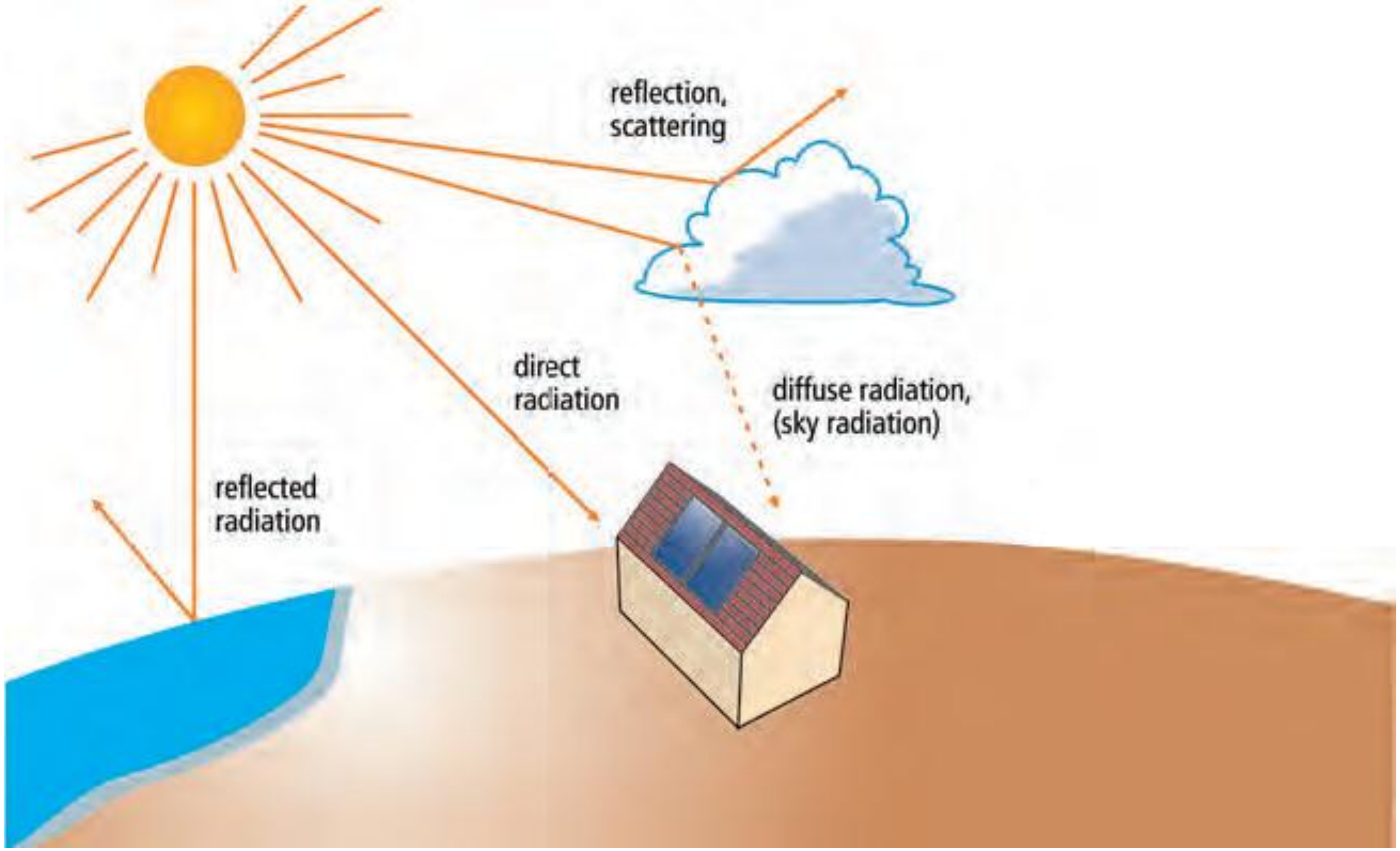
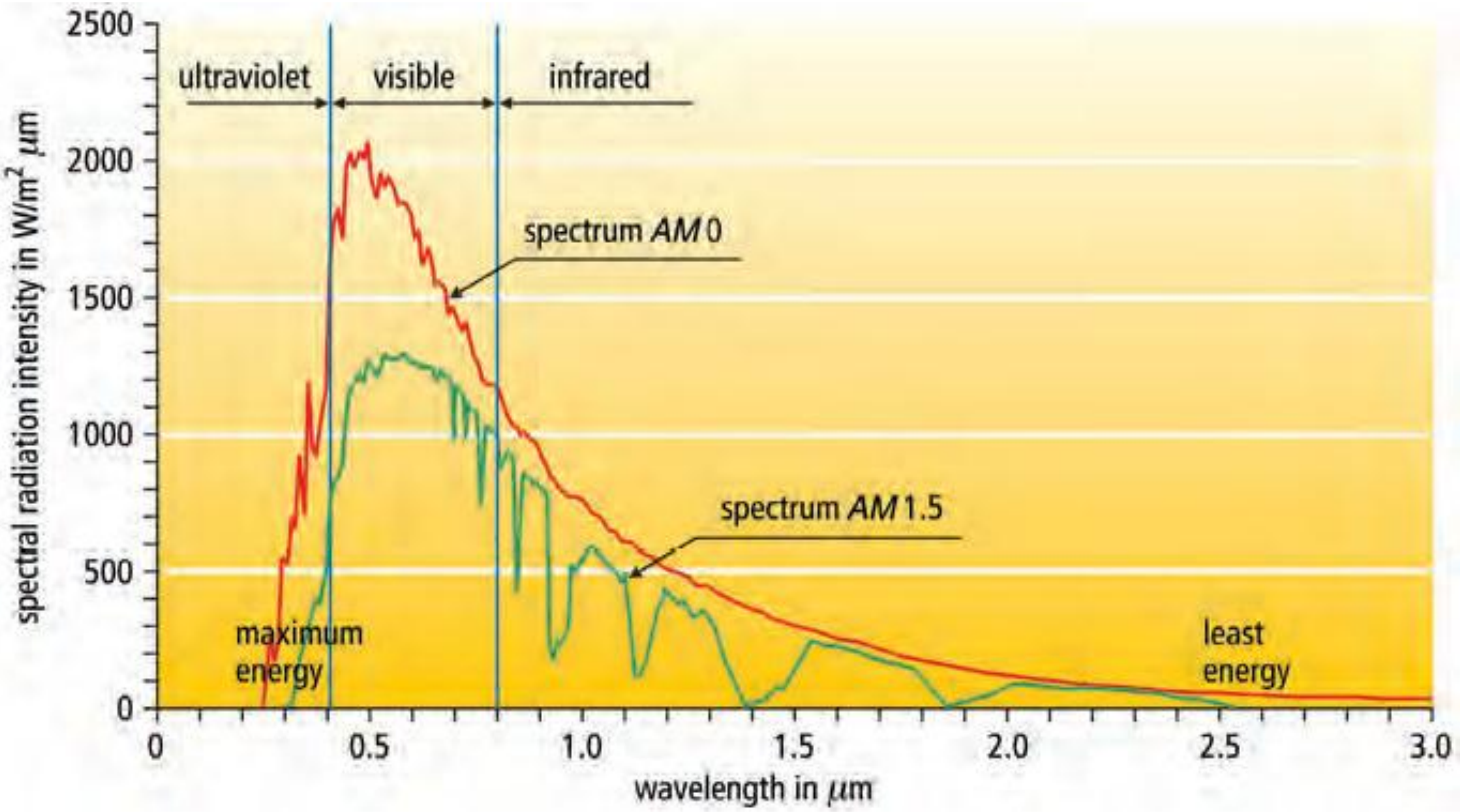


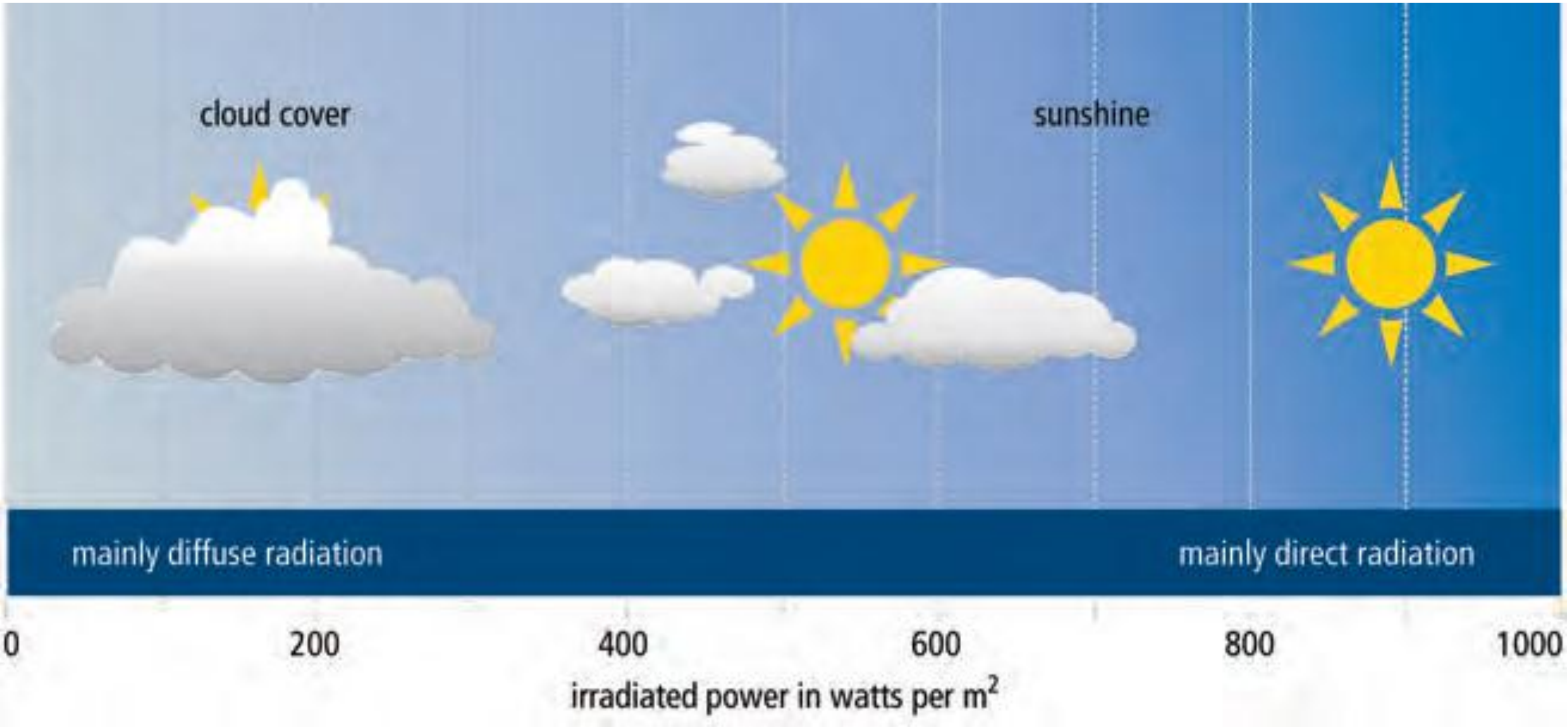
Figure 1.5.
Global solar irradiance and its components

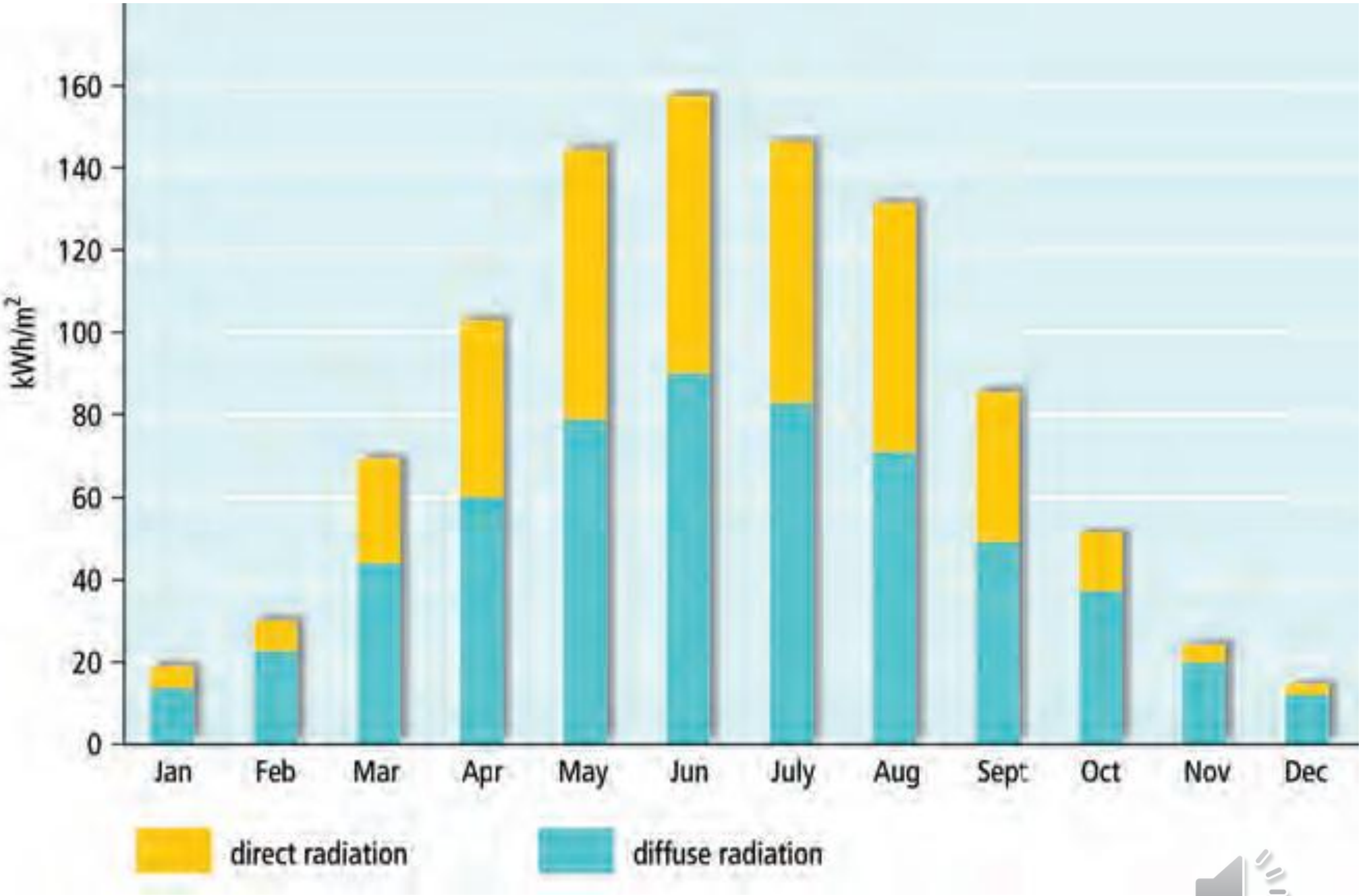
The sun’s radiation in space, without the influence of the earth’s atmosphere, is described as *spectrum AM 0*. As it passes through the earth’s atmosphere, the radiation intensity is reduced by:

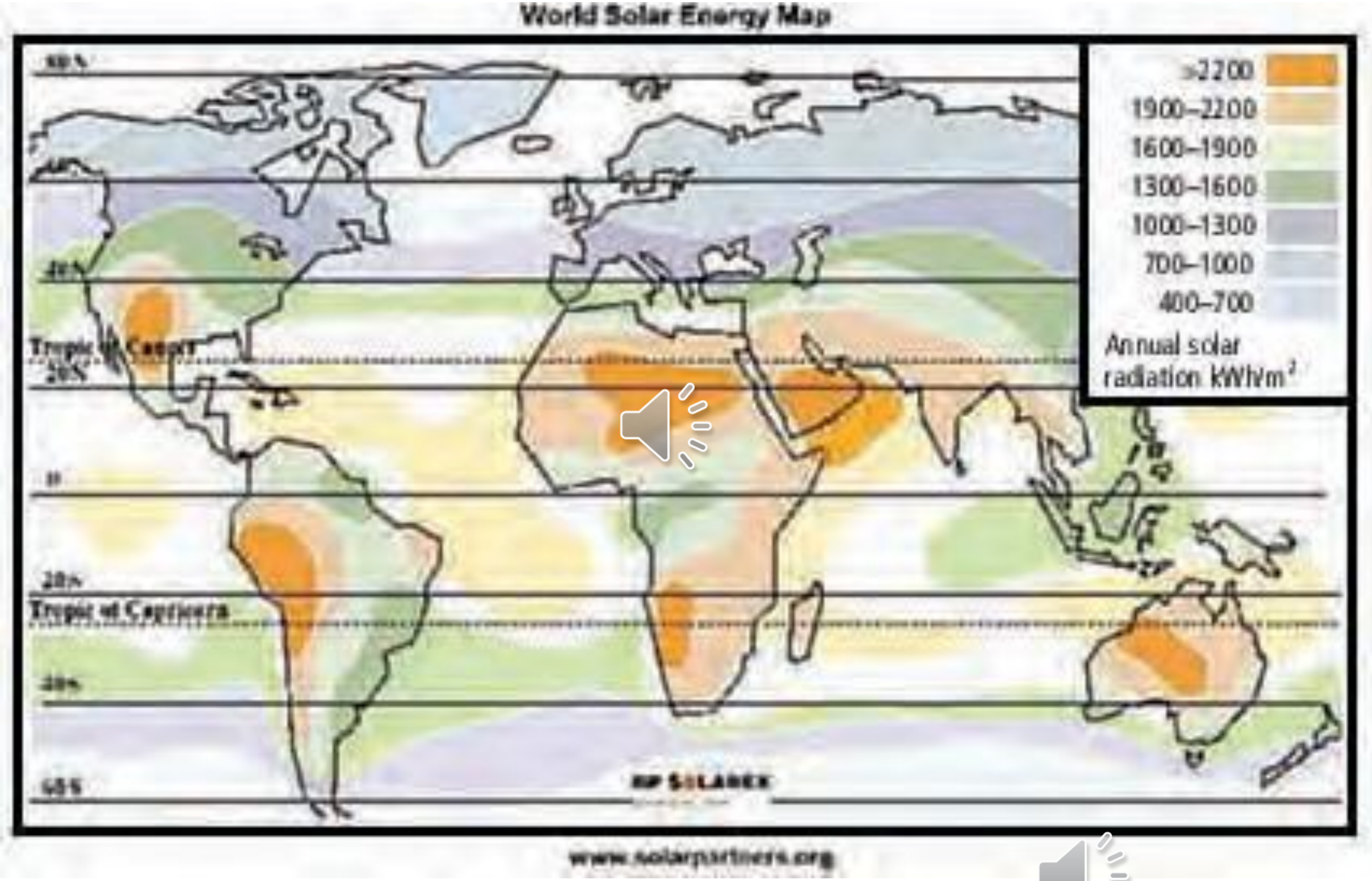
- reflection caused by the atmosphere
- absorption by molecules in the atmosphere (O3, H2O, O2, CO2)
- Rayleigh scattering (scattering by the air molecules)
- Mie scattering (scattering by dust particles and contamination in the air).

γS	**AM**	**Absorption (%)**	**Rayleigh scattering (%)**	**Mie scattering (%)**	**Total attenuation (%)**
90°	1.00	8.7	9.4	0–25.6	17.3–38.5
60°	1.15	9.2	10.5	0.7–25.6	19.4–42.8
30°	2.00	11.2	16.3	4.1–4.9	28.8–59.1
10°	5.76	16.2	31.9	15.4–74.3	51.8–85.4
5°	11.5	19.5	42.5	24.6–86.5	65.1–93.8


spectral radiation intensity in W/m^2 μm
2500
2000
1500
1000
500
0
ultraviolet
visible
infrared
spectrum *AM* 0
spectrum *AM* 1.5
maximum energy
least energy
0
0.5
1.0
1.5
2.0
2.5
3.0
wavelength in μm


cloud cover
sunshine
mainly diffuse radiation
mainly direct radiation
0
200
400
600
800
1000
irradiated power in watts per m²


kWh/m²
160
140
120
100
80
60
40
20
0
Jan
Feb
Mar
Apr
May
Jun
July
Aug
Sept
Oct
Nov
Dec
direct radiation
diffuse radiation


World Solar Energy Map
60°N
40°N
Tropic of Cancer
20°N
0
20°S
Tropic of Capricorn
40°S
60°S
>2200
1900–2200
1600–1900
1300–1600
1000–1300
700–1000
400–700
Annual solar radiation kWh/m²
BP SOLAREX
www.solarpartners.org

MEASURING SOLAR RADIATION

Devices that measure the global solar irradiance on a horizontal surface are called pyranometers (Figure 1.11). If these devices are screened from the sun’s direct rays by a fixed ring that covers the whole path of the sun in the sky, then the device measures only the diffused radiation.

The radiation receiver is seated beneath a spherical glass cover and consists of a star-shaped arrangement of black and white thermo-elements. These elements generate thermo-electromotive forces, depending on their temperature, which can be measured.

Pyranometers are relative measuring instruments that have to be calibrated. Other global solar irradiance measuring devices that are available on the market and are cheaper than pyranometers possess a solar cell as a receiver, as in the MacSolar (Figure 1.12), for example.

The simplest and most commonly used device for measuring the sunshine duration is the Campbell–Stokes sunshine recorder (Figure 1.13).

This consists of a solid glass sphere, which generates a focal point on the side that is turned away from the sun and which is always at the same distance. A correspondingly curved flameproof paper strip is placed around the sphere. A track is burned on the paper strip. When clouds cover the sun, the burnt track is interrupted.

Figure 1.11.
Pyranometer made by Kipp & Zonen

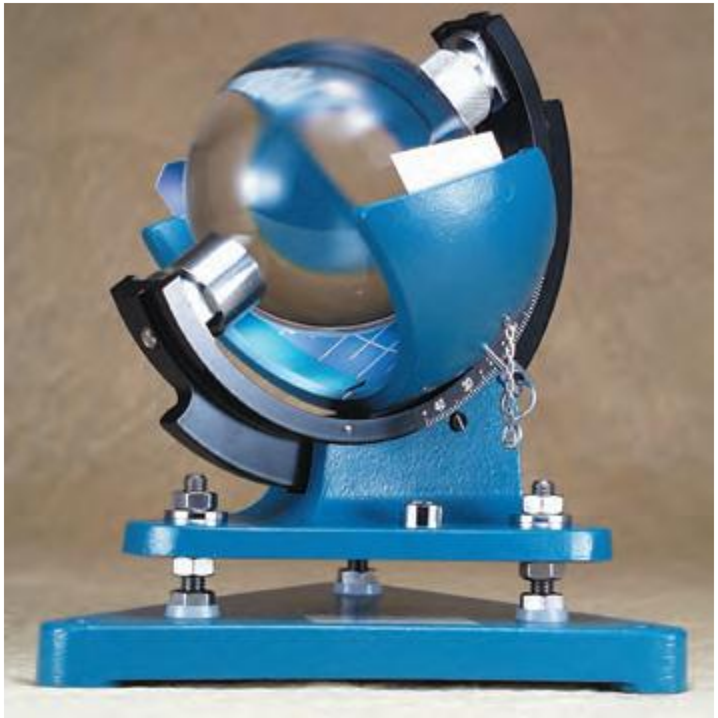
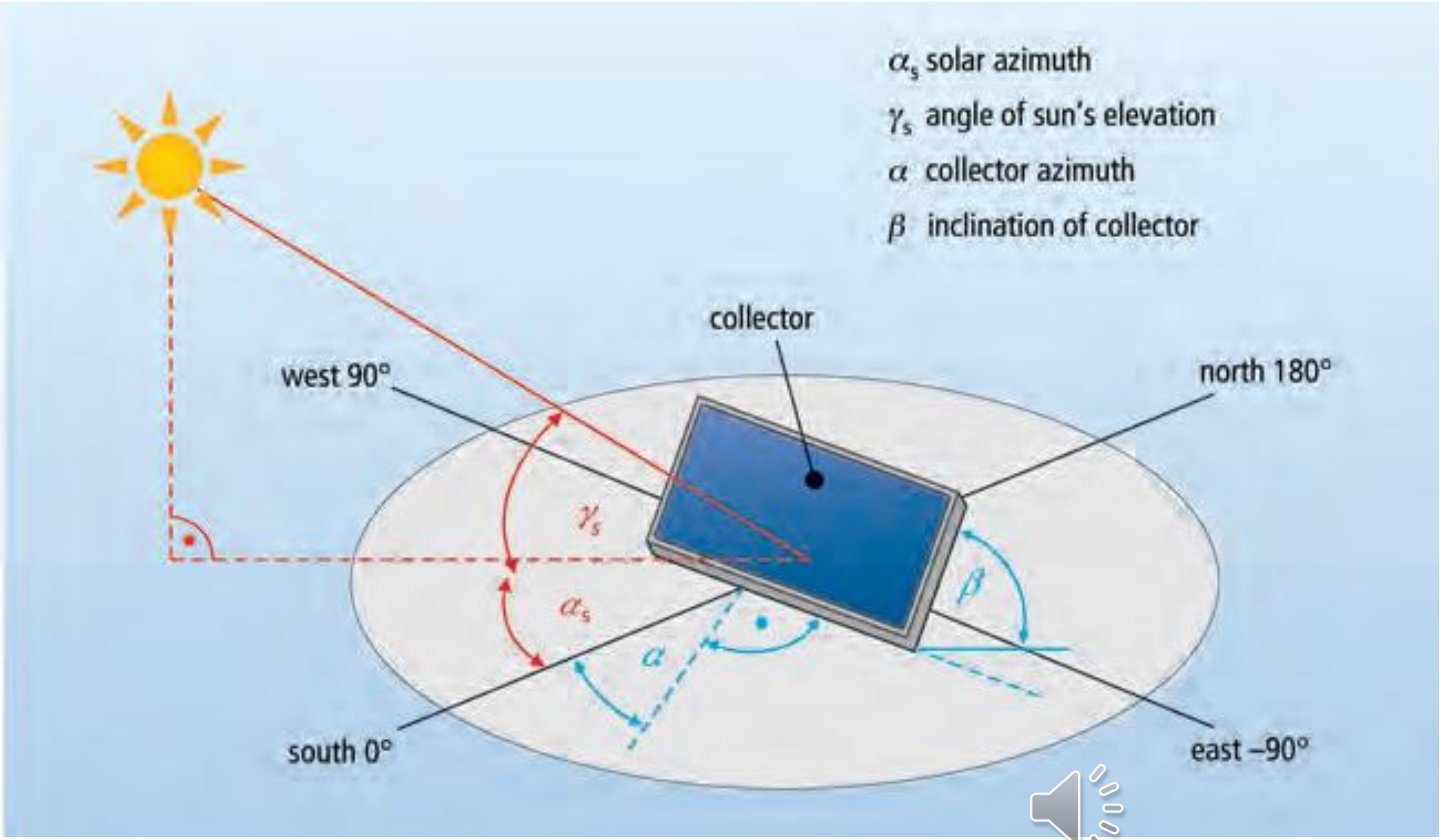


Figure 1.12 (left).
MacSolar

Figure 1.13 (right).
Campbell–Stokes sunshine recorder


α_s solar azimuth
γ_s angle of sun's elevation
α collector azimuth
β inclination of collector
collector
west 90°
north 180°
γ_s
α_s
α
β
south 0°
east –90°

SHADING

Shading reduces the yield of a solar thermal system. To take account of shading of the receiving surface by the surroundings (houses, trees etc.), three methods can be used:

- graphical method (indicative)
- photographic method (indicative)
- computer-aided method.

GRAPHICAL METHOD

This method requires a scale drawing of the layout of the surroundings, details of the height of each object that could shade the potential collector position, and a solar altitude diagram for the latitude at which the collector is to be located.

First, the elevation and azimuth angles of the relevant objects must be established, and then the shade silhouette must be plotted in the solar altitude diagram. If large areas of shade arise in time periods with high radiation, then the expected radiation received must be reduced correspondingly.

PHOTOGRAPHIC METHOD

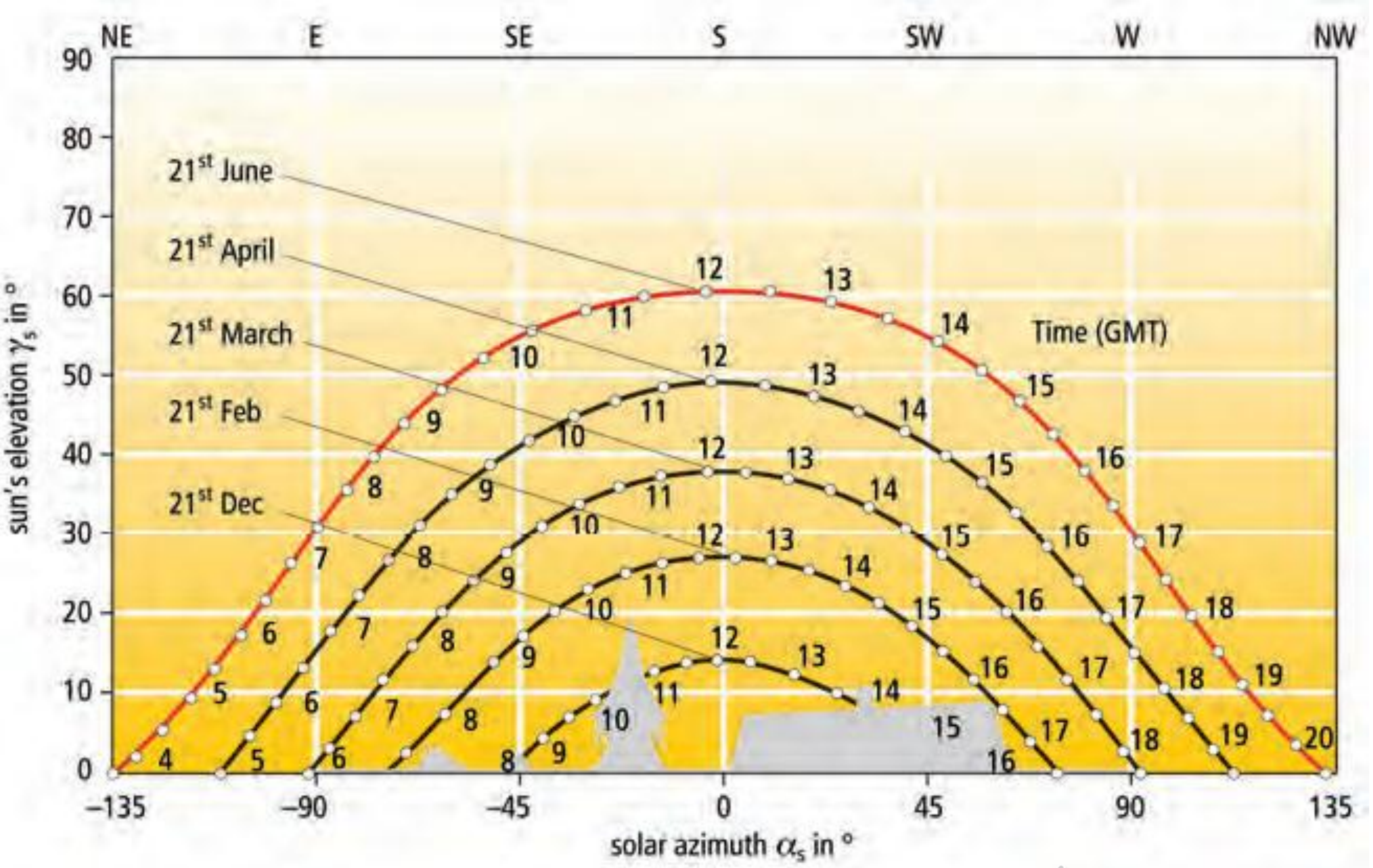
In this method a camera with a ‘fish-eye’ lens is used in connection with special solar-geometrical accessories to photograph the surrounding silhouette while blending in the solar altitude diagram of the respective location.

The results can then be read directly off the photograph.

COMPUTER-AIDED METHOD

Several simulation programs are provided with shade simulators (see for instance TRNSYS and Sundi in Chapter 10). After determining the elevation and azimuth angles of important objects, the influence of shade can be directly calculated within the scope of the system simulation.

This method yields more accurate results than the previous two methods.
Figure 1.16 shows an example of a solar altitude diagram with surrounding silhouette.


NE
E
SE
S
SW
W
NW
sun's elevation γ_s in °
solar azimuth α_s in °
21st June
21st April
21st March
21st Feb
21st Dec
Time (GMT)
90
80
70
60
50
40
30
20
10
0
–135
–90
–45
0
45
90
135

The solar collector mounted on the roof converts the light that penetrates its glass panes (short-wave radiation) into heat.

The collector is therefore the link between the sun and the hot water user. The heat is created by the absorption of the sun’s rays through a dark-coated, usually metal, plate – the *absorber*.

This is the most important part of the collector. In the absorber is a system of pipes filled with a *heat transfer medium* (usually water or an antifreeze mixture). This takes up the generated heat.

Collected together into a pipe it flows to the *hot water store*. In most solar water heating systems – by far the most commonly used type of solar thermal systems – the heat is then transferred to the domestic water by means of a *heat exchanger*. The cooled medium then flows via a second pipeline back to the collector while the heated domestic water rises upwards in the store.

According to its density and temperature, a *stratified system* is set up in the store: the warmest water is at the top (from where it leaves the tank when the taps are turned on) and the coldest is at the bottom (where cold water is fed in).

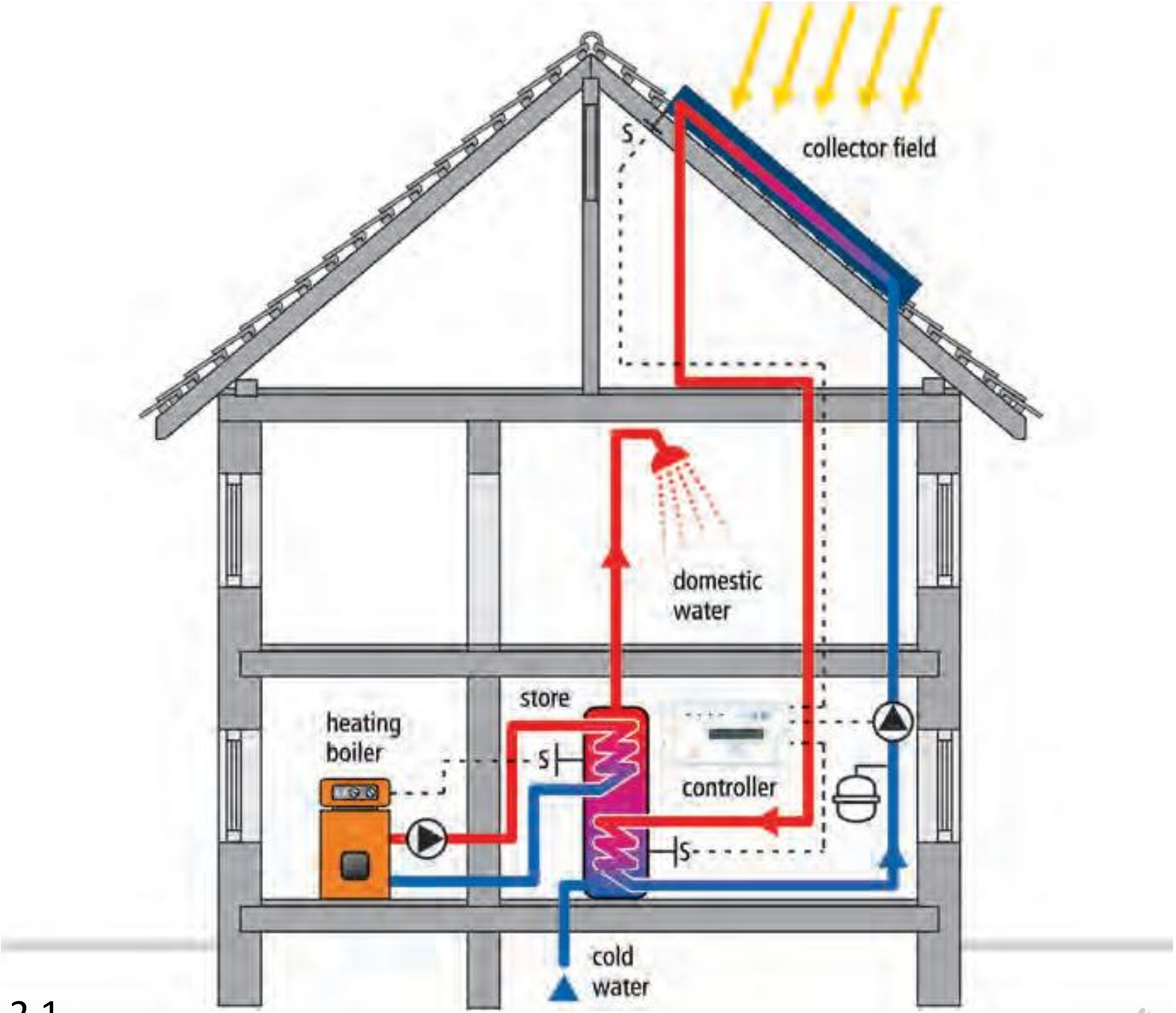


Figure 2.1.
Standard solar water heating system with heating boiler for additional heating
(S = temperature sensor)

Figure 2.2.

Standard thermosyphon solar water heater with outdoor tank
Source: Solahart

For temperate climates, in a solar system for one- and two-family homes with dimensions of about 0.6–1.0 m2 (6.46–10.76 ft2) of collector surface per person and approximately 40–60 l (10.6–15.9 gallons) of storage volume per person, the water is mostly heated by the solar system in the summer.

This provides an annual degree of coverage (proportion of solar energy to the total energy required for domestic water heating) of about 50–60%. The remaining 40–50% has to be covered by auxiliary heating.

For pumped systems, this is often done by means of an extra heat exchanger in the top of the store. Other common solutions are to use the solar water heater as a preheater and connect the solar-heated water to a conventional boiler, or (mainly for sunny climates) to use an electrical element immersed in the store.

Another decisive factor in establishing the level of supplementary energy required is the target domestic water temperature on the boiler controller. The lower this is set, for example 45°C (113°F), the higher the coverage proportion of solar energy and correspondingly the lower the proportion of auxiliary energy, and vice versa. However, in some countries, domestic hot water regulations pose a lower limit on this temperature setting, of 60°C (140°F).

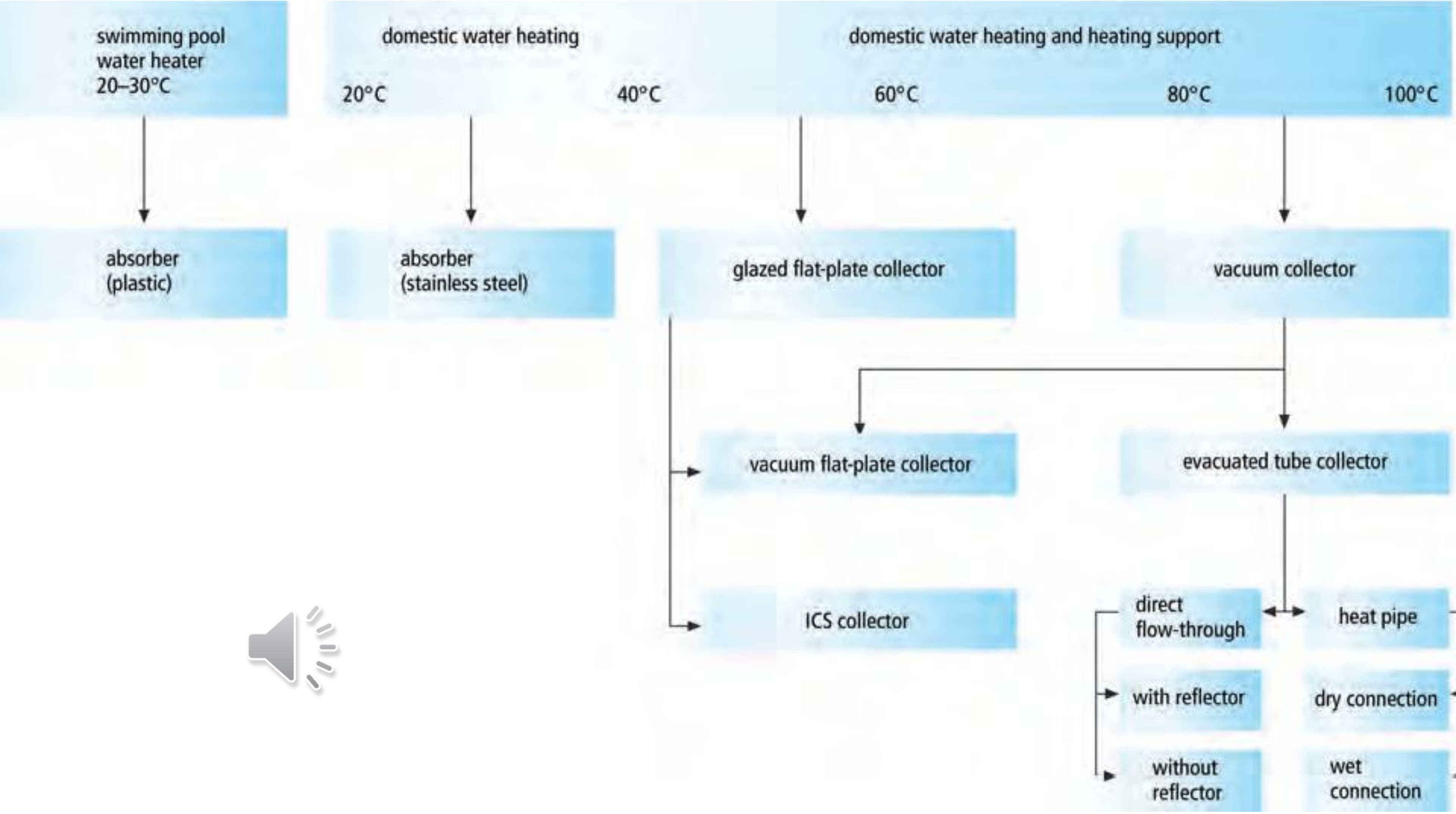
Collectors have the task of converting light as completely as possible into heat, and then of transferring this heat with low losses to the downstream system.

There are many different types and designs for different applications, all with different costs and performances. See Figures 2.3 and 2.4.

Different definitions of area are used in the manufacturers’ literature to describe the geometry of the collectors, and it is important not to confuse them:

- The *gross surface area* (collector area) is the product of the outside dimensions, and defines for example the minimum amount of roof area that is required for mounting.

- The *aperture area* corresponds to the light entry area of the collector – that is, the area through which the solar radiation passes to the collector itself.



swimming pool
water heater
20–30°C

domestic water heating

domestic water heating and heating support

20°C

40°C

60°C

80°C

100°C

absorber
(plastic)

absorber
(stainless steel)

glazed flat-plate collector

vacuum collector

vacuum flat-plate collector

evacuated tube collector

ICS collector

direct
flow-through

heat pipe

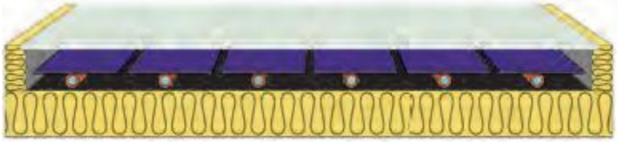
with reflector

dry connection

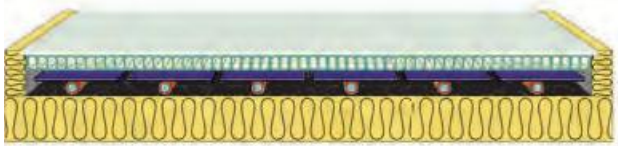
without
reflector

wet
connection


unglazed collector, absorber


standard flat collector


collector with limited convection


collector with transparent heat insulation


vaccum flat-plate collector (with pillars)


air collector

The *absorber area* (also called the *effective collector area*) corresponds to the area of the actual absorber panel. See Figures 2.5–2.7.

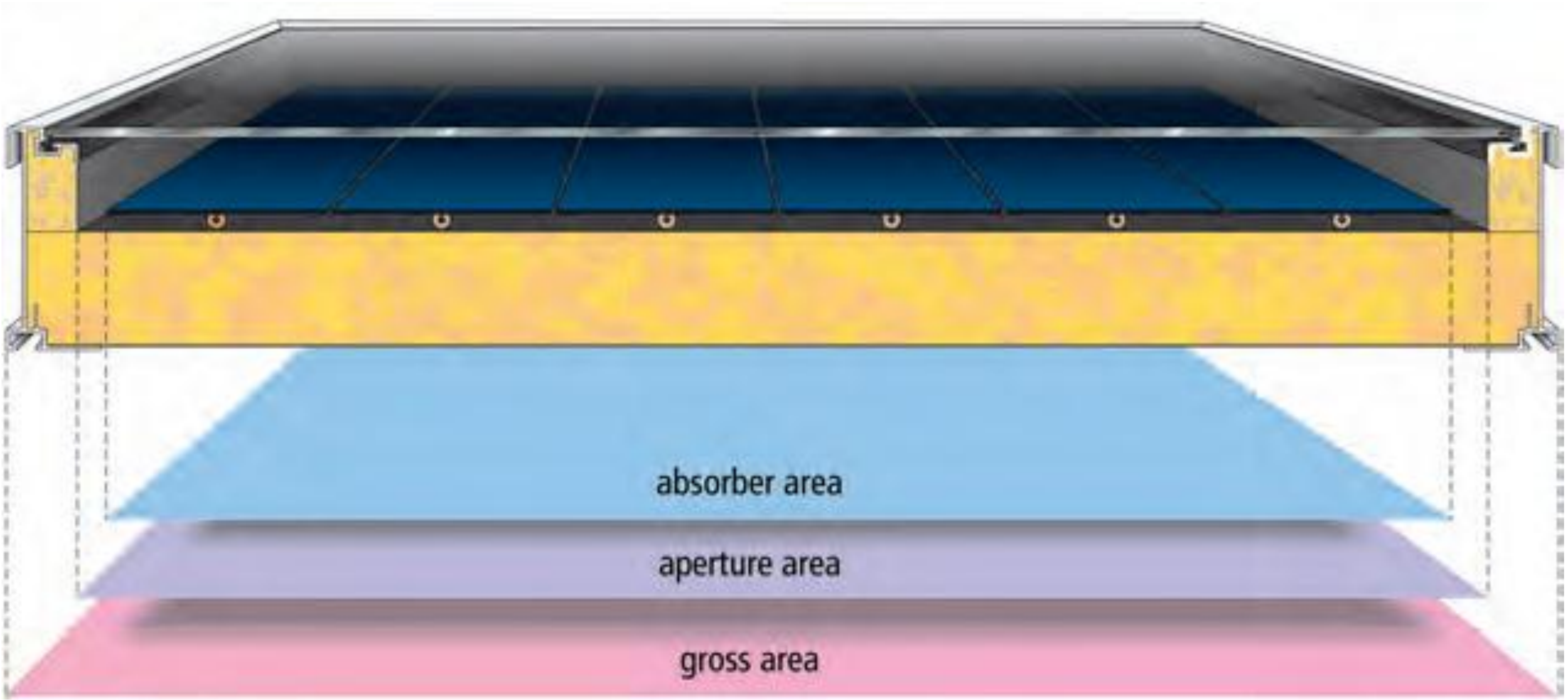


Figure 2.5.
Cross-section of a flat-plate collector with description of the different areas

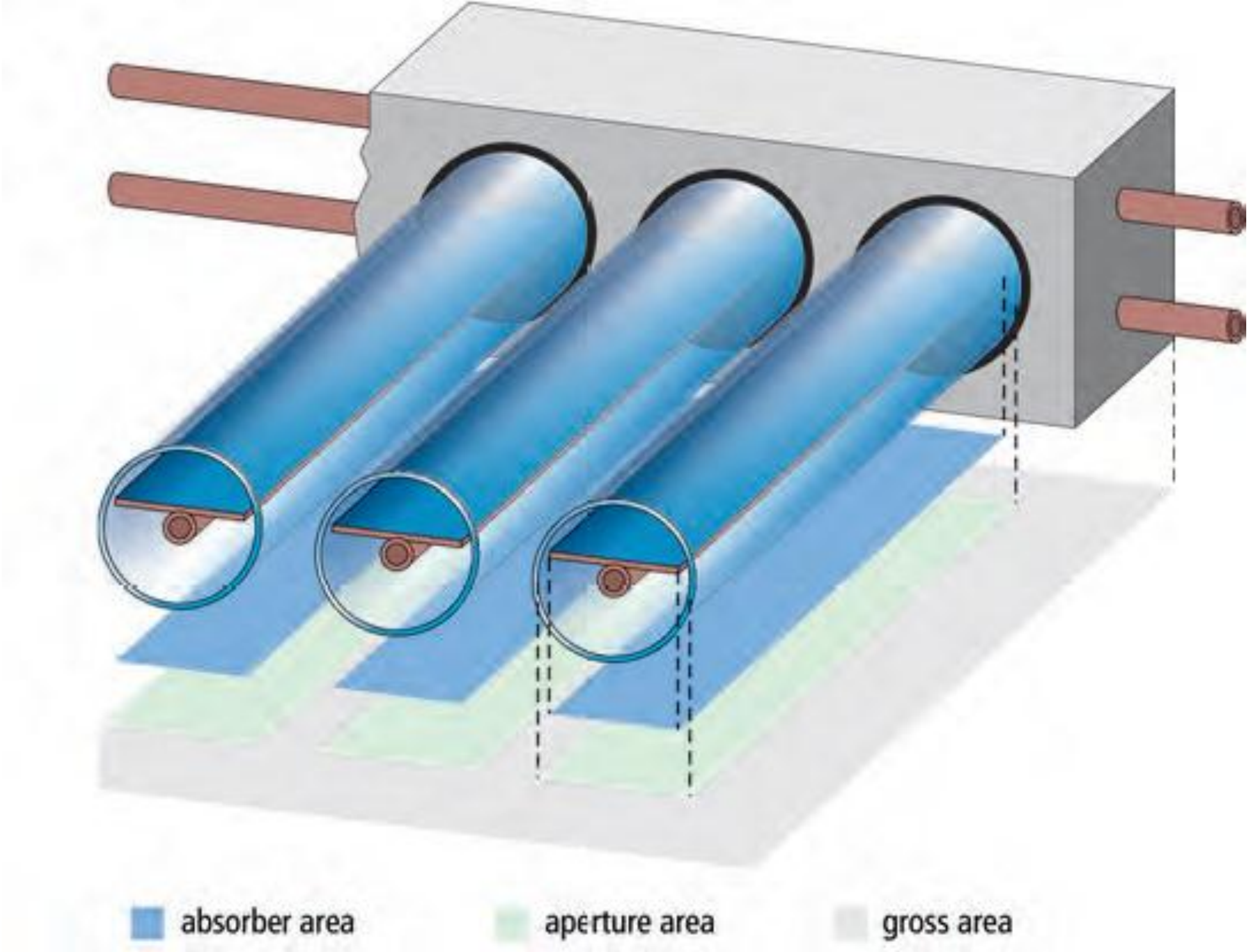


Figure 2.6.
Cross-section of a heat-pipe evacuated tube collector with description of the different surface areas

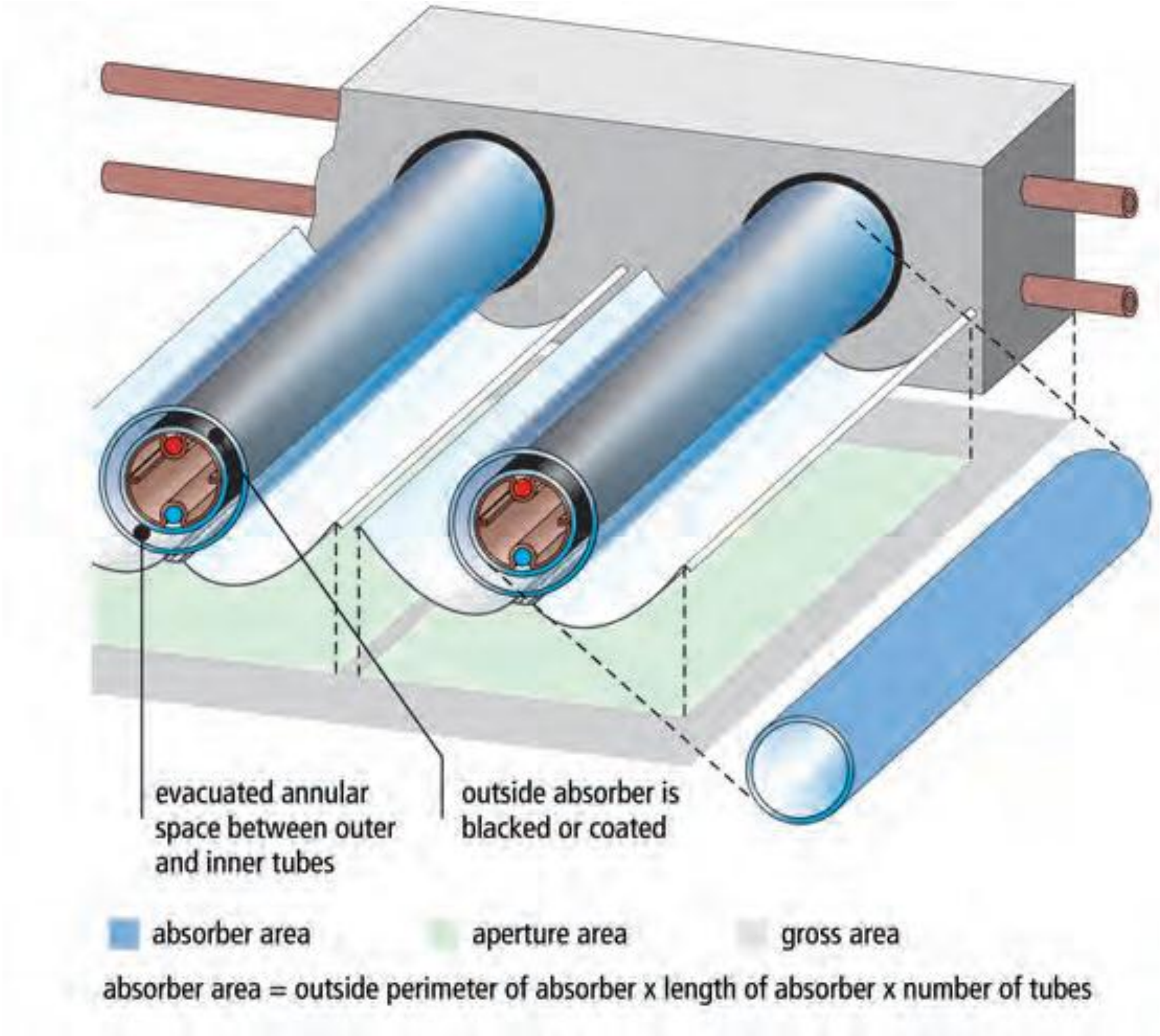


Figure 2.7.

Cross-section of a double evacuated tube collector (‘Sydney tubes’) with description of the different surface areas

2.2.2 Glazed flat-plate collectors

2.2.2.1 DESIGN

Almost all glazed flat-plate collectors currently available on the market consist of a metal absorber in a flat rectangular housing. The collector is thermally insulated on its back and edges, and is provided with a transparent cover on the upper surface. Two pipe connections for the supply and return of the heat transfer medium are fitted, usually to the side of the collector. See Figure 2.8.

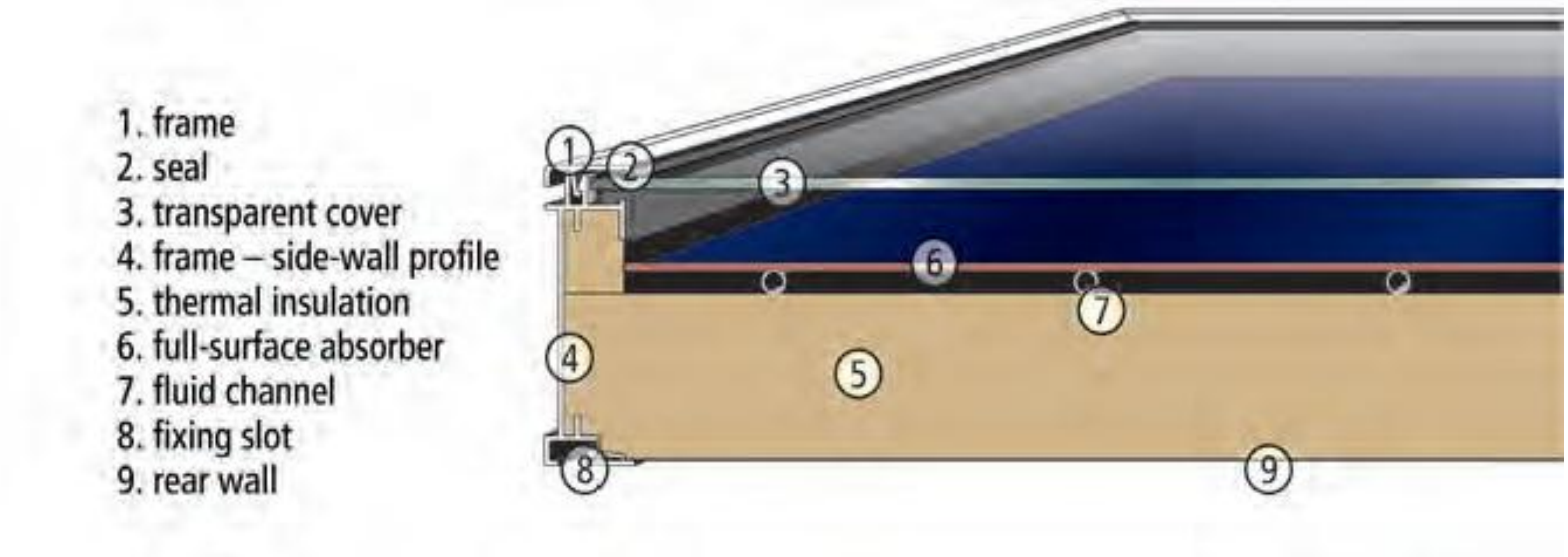


Figure 2.8.
Section through a glazed flat-plate collector

ABSORBER

The core piece of a glazed flat-plate collector is the *absorber*. This consists of a heatconducting metal sheet (made of copper or aluminium for example, as a single surface or in strips) with a dark coating. The tubes for the heat transfer medium, which are usually made of copper, are connected conductively to the absorber.

When the solar radiation hits the absorber it is mainly absorbed and partially reflected. Heat is created through the absorption and conducted in the metal sheet to the heat transfer medium tubes or channels. Through these tubes flows the liquid heat transfer medium, which absorbs the heat and transports it to the store.

A variant is the so-called *cushion absorber*, which has full-surface flow-through. The task of a solar collector is to achieve the highest possible thermal yield. The absorber is therefore provided with a high light-absorption capacity and the lowest possible thermal emissivity. This is achieved by using a *spectral-selective coating*.

Unlike black paint, this has a layered structure, which optimizes the conversion of short-wave solar radiation into heat while keeping the thermal radiation as low as possible. See Figure 2.9.

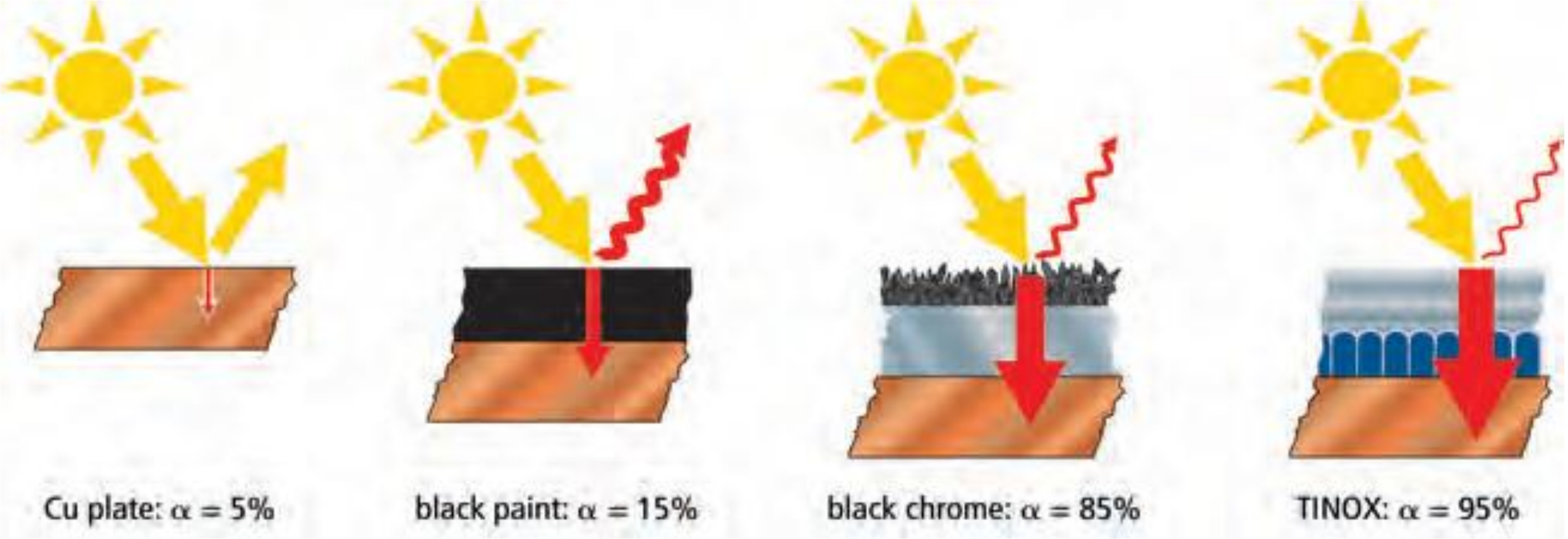


Figure 2.9.
Absorption and emission behaviour of different surfaces

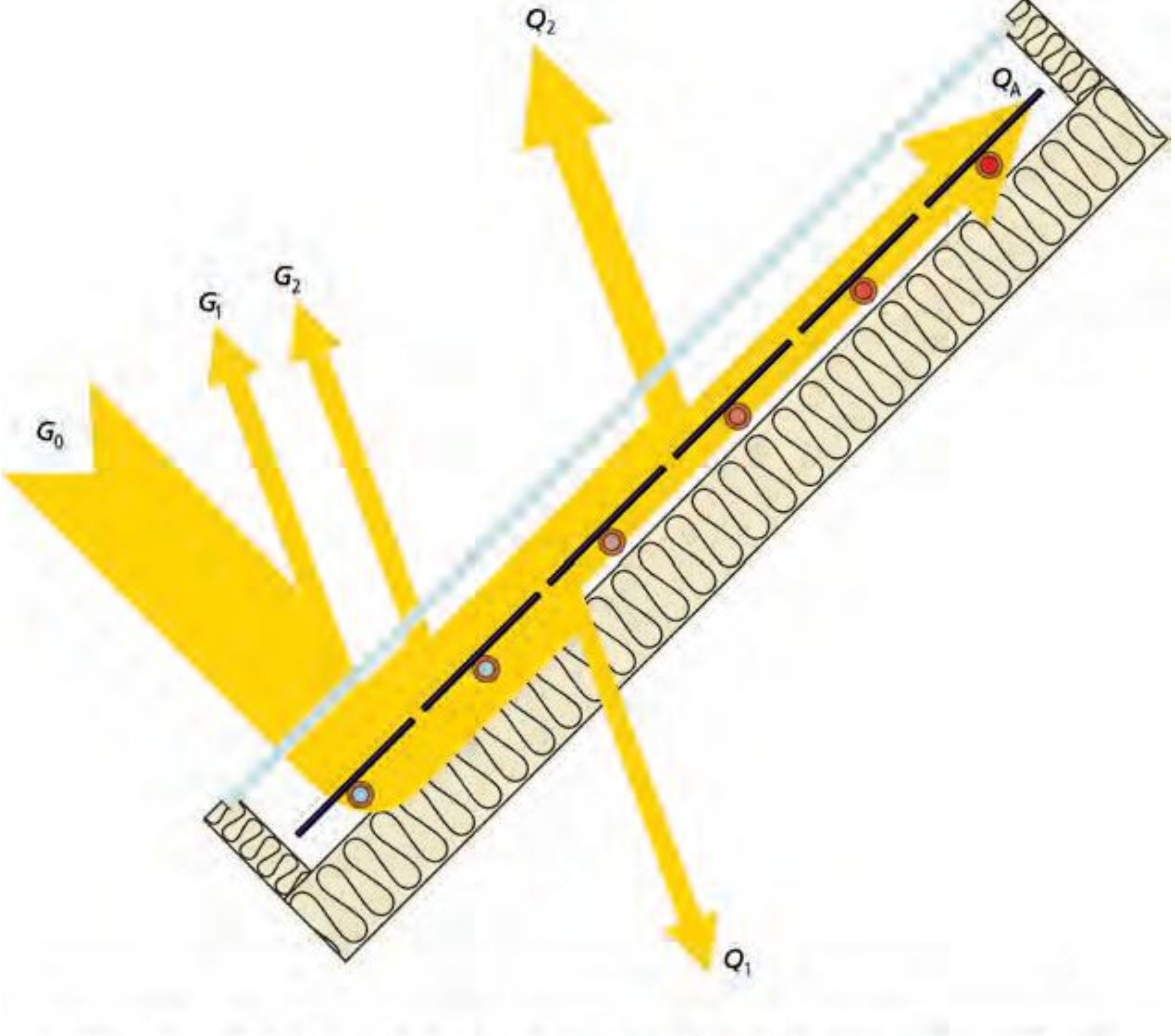
RADIATION AND INTERACTION WITH MATTER

When short-wave sunlight (wavelength 0.3–3.0 m) hits an object, such as a solar cover, it is reflected more or less strongly according to the surface structure (material, roughness and colour).

White surfaces reflect much more than dark surfaces. The proportion of reflected radiation (especially for glass panes) also depends on the angle of incidence of the radiation (Fresnel’s law).

The remaining portion is absorbed by the object or, for translucent material, is allowed to partially pass through.

Finally, the absorbed portion is converted into long-wave thermal radiation (wavelengths 3.0–30 m) and radiated according to the surface structure.
These processes are described physically as the degrees of reflection, absorption, transmission and emissivity of a body



irradiance (G_0) – reflection losses (G_1 and G_2) – thermal losses ($\dot{Q}_1$ and $\dot{Q}_2$) – available heat quantity ($\dot{Q}_A$)

Figure 2.10.
Energy flows in the collector

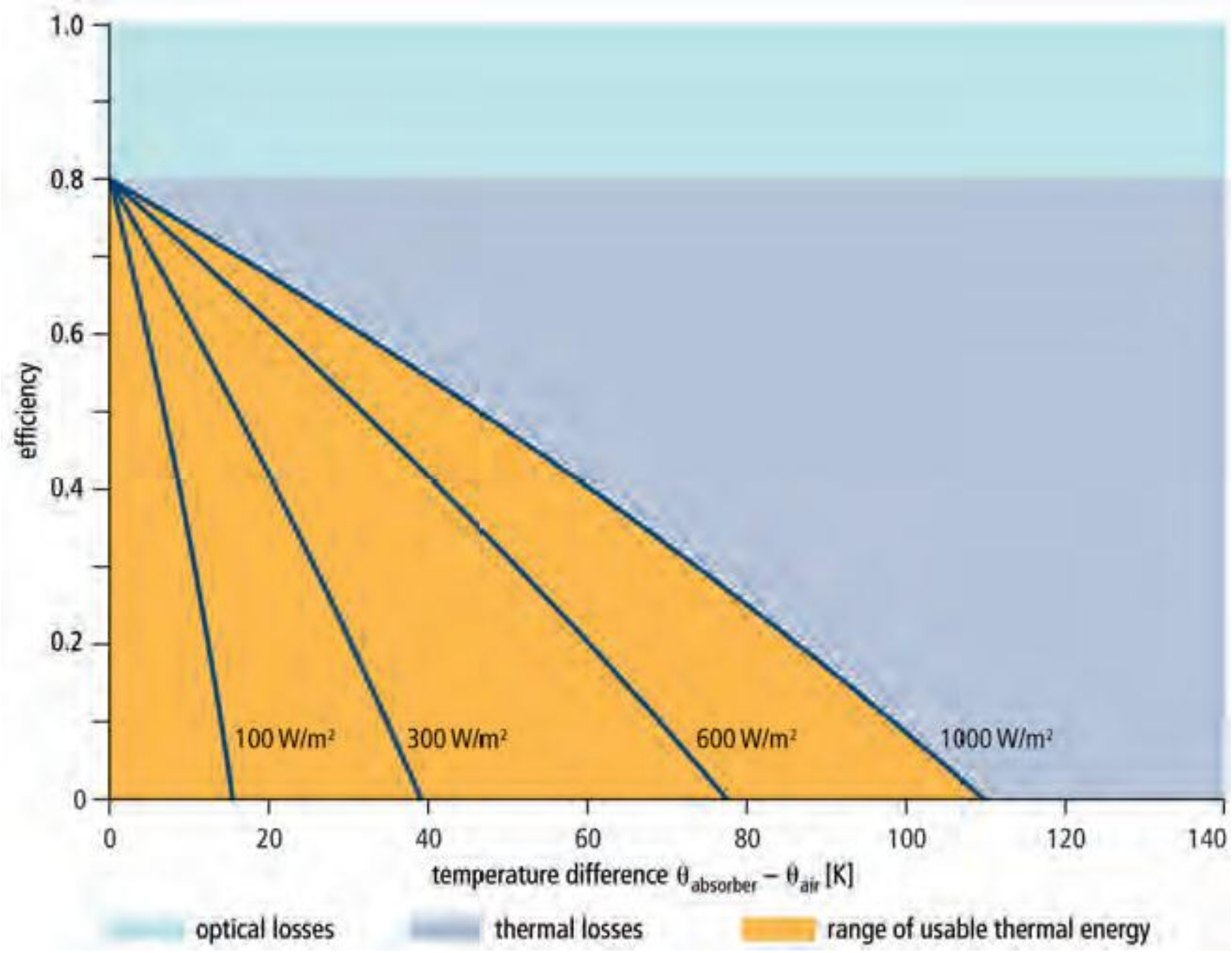
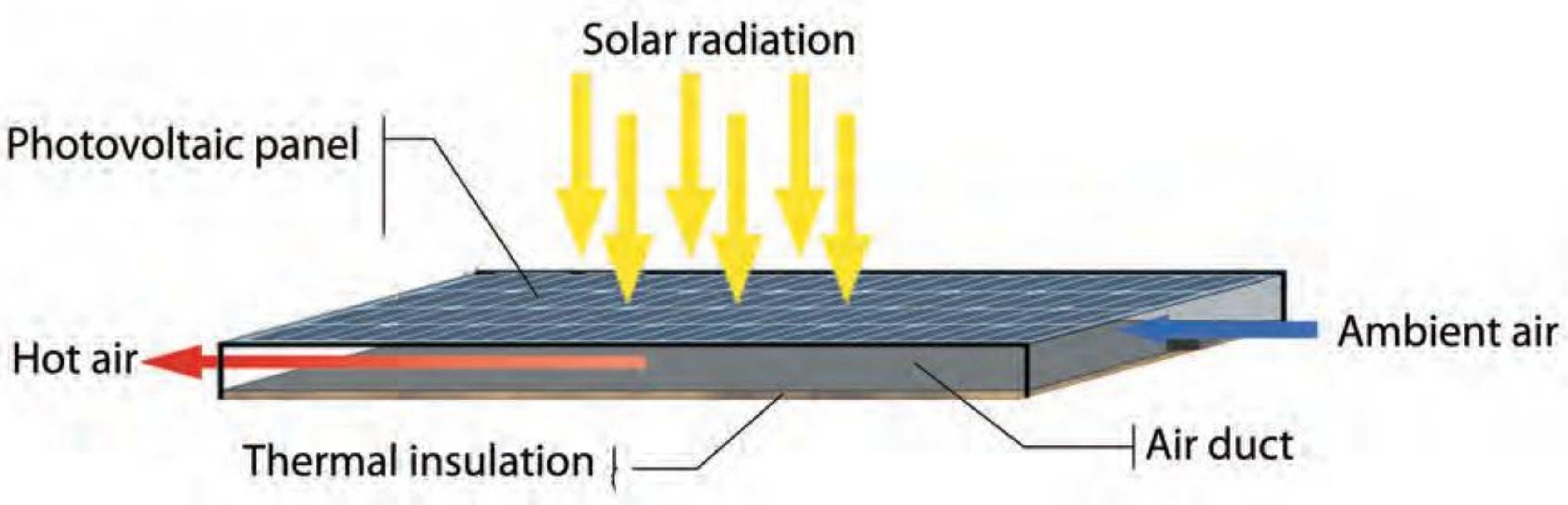
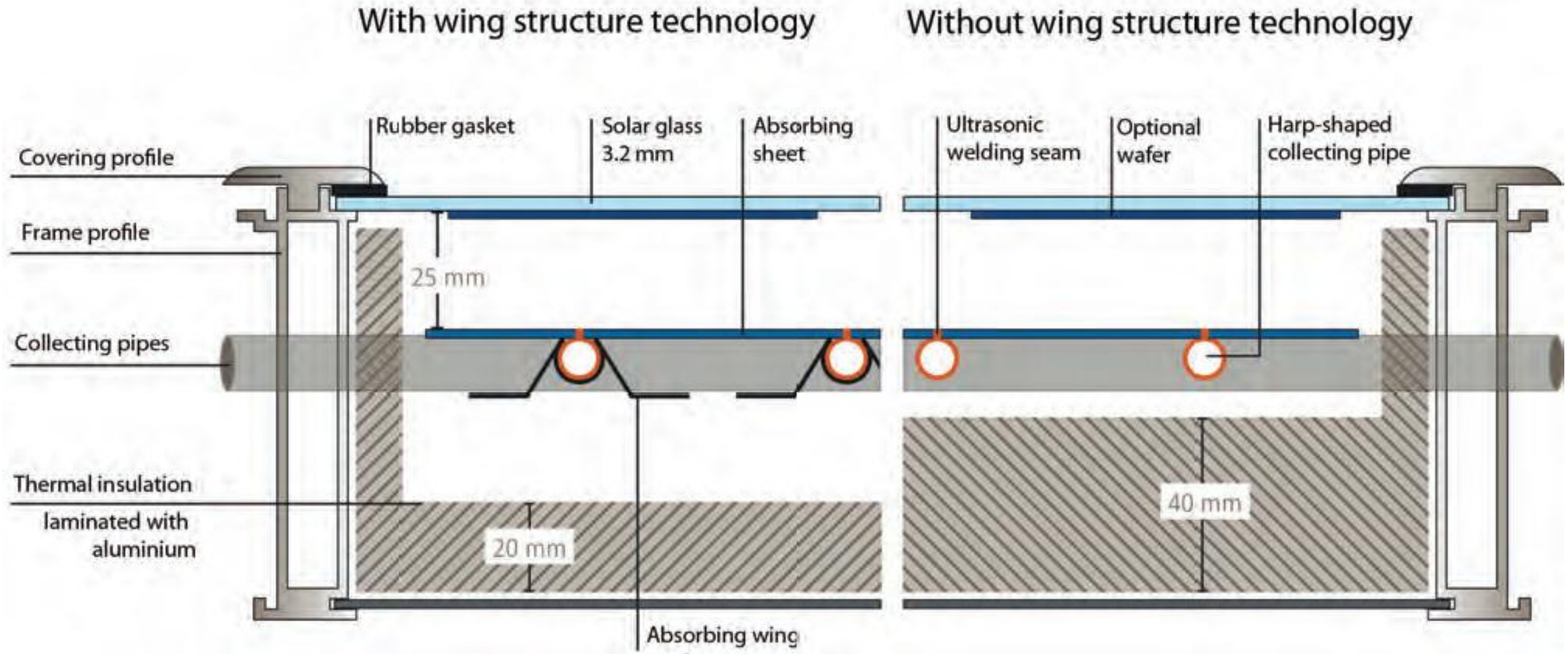


Figure 2.11.
Optical and thermal losses

HYBRID COLLECTOR

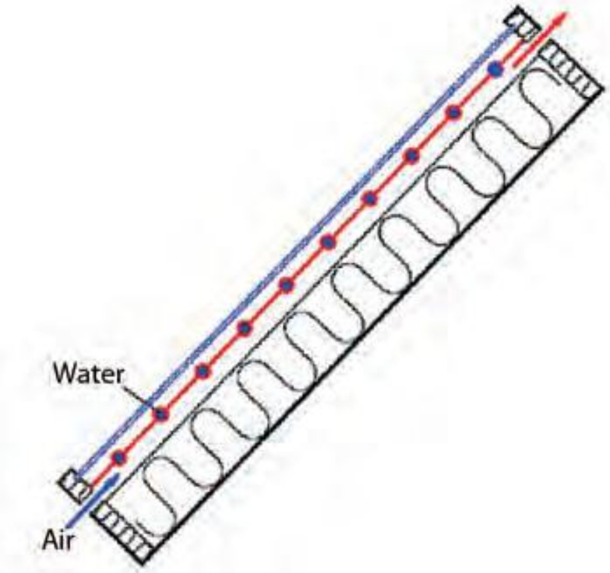
Hybrid collectors can be realized as a combination of solar panels (PV) with liquidbased collectors as well as with air-based collectors. The combination with solar panels is reasonable, because during the solar electricity conversion only about 12% (with crystalline silicon) of the solar radiation converts into electricity, whereas the remainder converts into heat. This heat is used in the hybrid collector to either heat up a liquid or air (see Section 8.2.1.8).





With wing structure technology

Without wing structure technology



2.2.3 Vacuum collectors

2.2.3.1 EVACUATED TUBE COLLECTORS

To reduce the thermal losses in a collector, glass cylinders (with internal absorbers) are evacuated in a similar way to Thermos flasks (Figure 2.17). In order to completely suppress thermal losses through convection, the volume enclosed in the glass tubes must be evacuated to less than 10–2 bar (1 kPa).

Additional evacuation prevents losses through thermal conduction.

The radiation losses cannot be reduced by creating a vacuum, as no medium is necessary for the transport of radiation.

They are kept low, as in the case of glazed flat-plate collectors, by selective coatings (small value).

The heat losses to the surrounding air are therefore significantly reduced. Even with an absorber temperature of 120°C (248°F) or more the glass tube remains cold on the outside.

Most vacuum tubes are evacuated down to 10–5 bar.

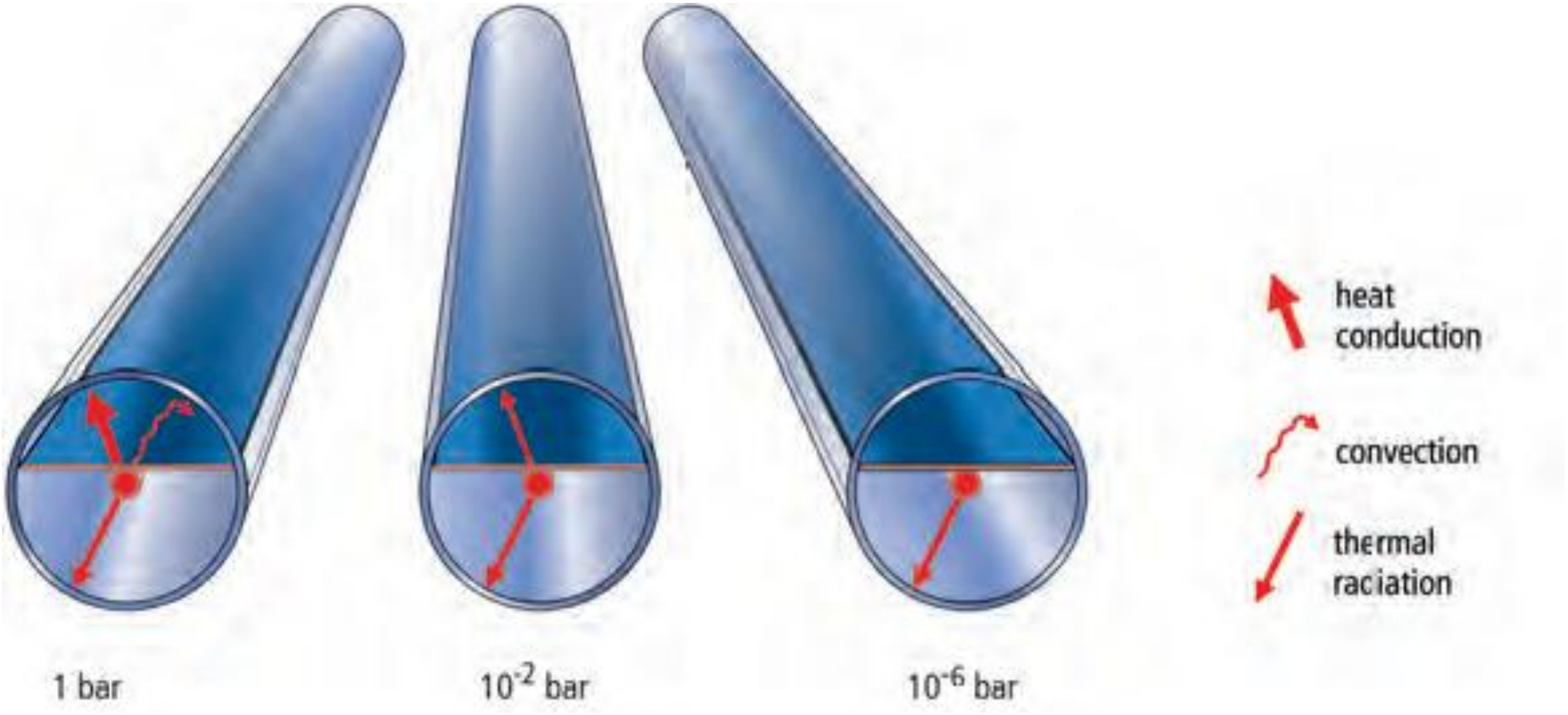


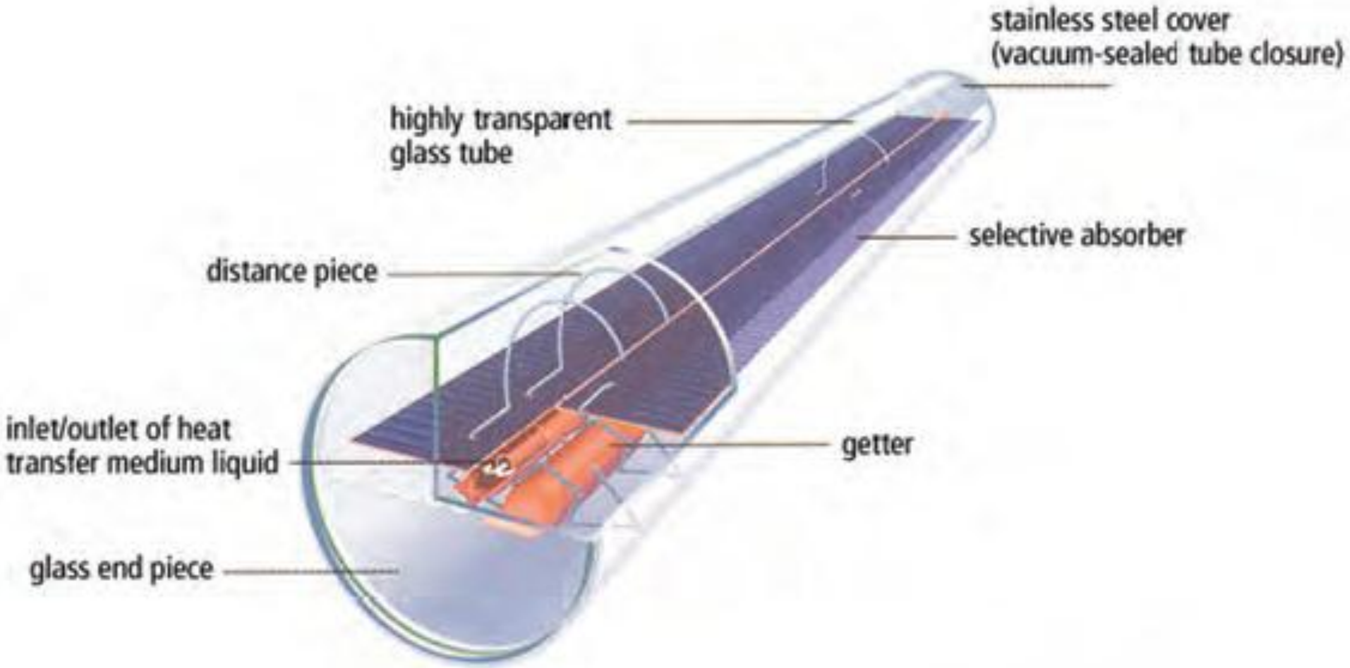
Figure 2.17.

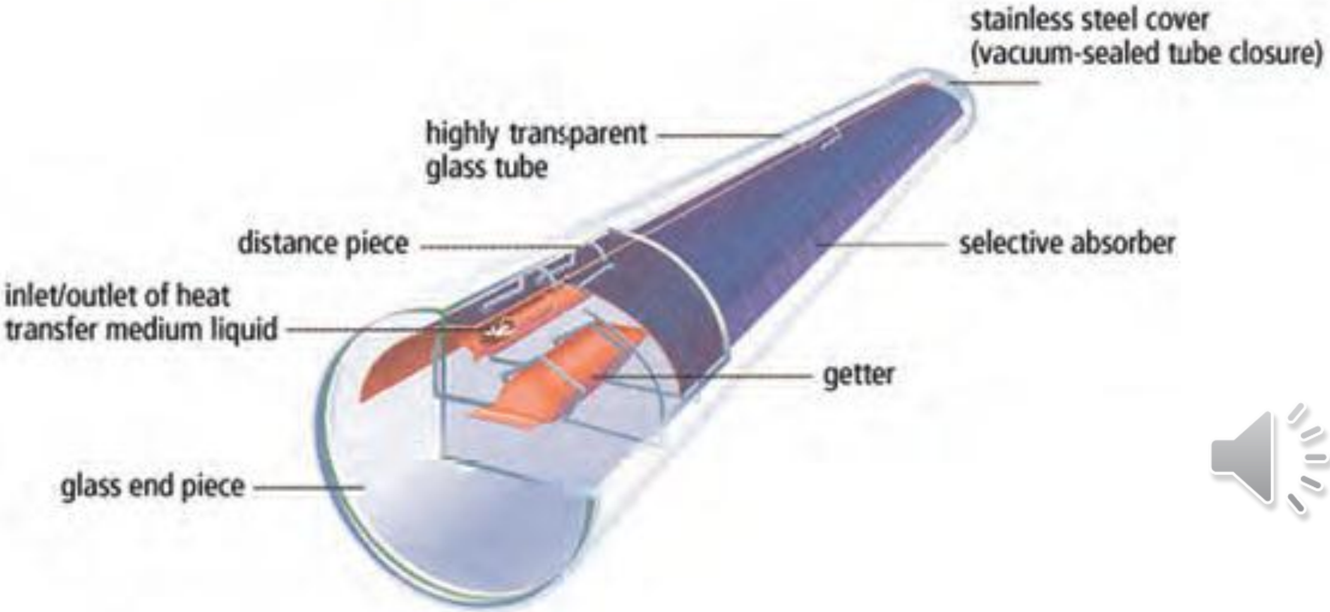
The principle of vacuum thermal insulation

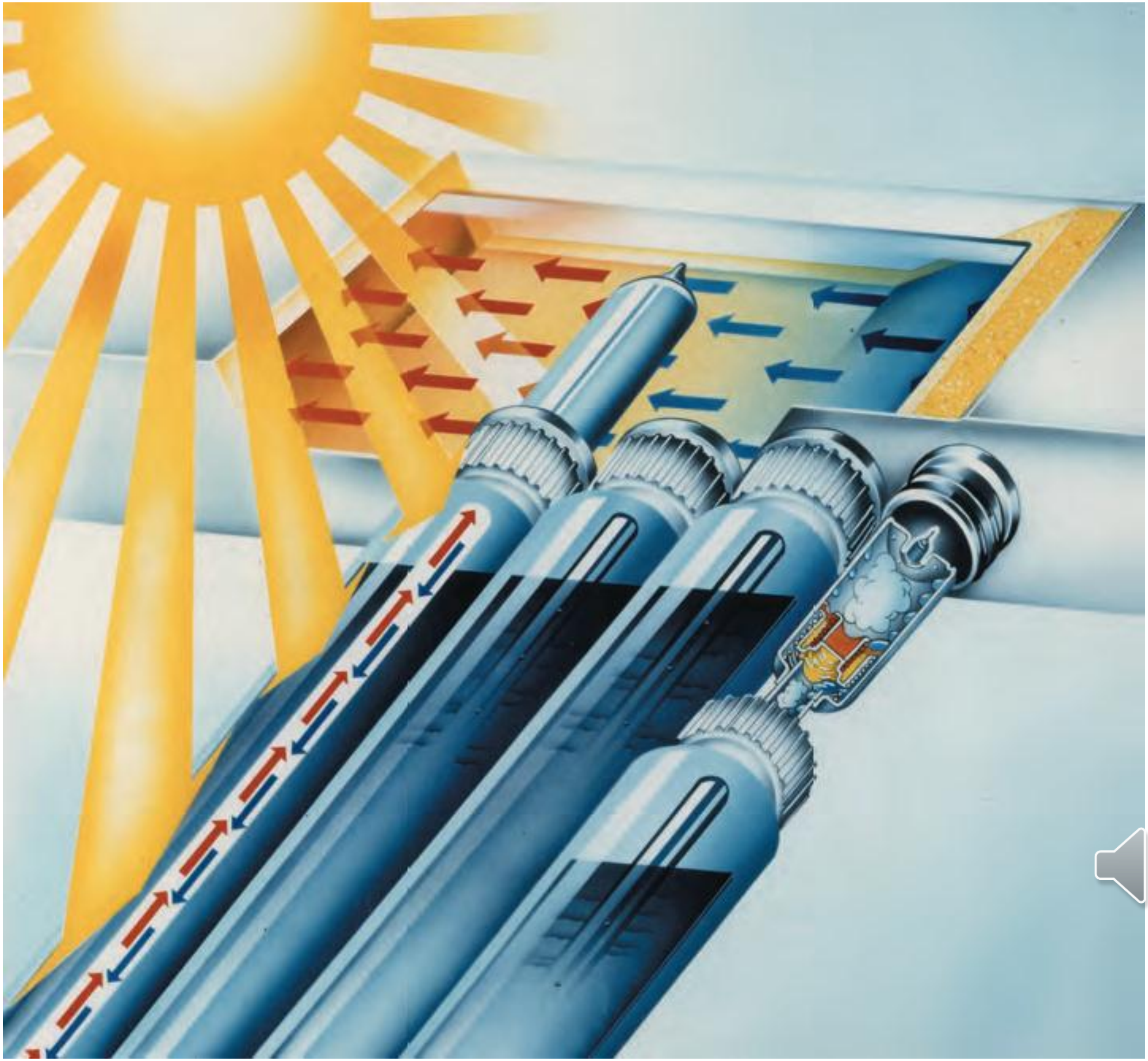
DIRECT FLOW-THROUGH EVACUATED TUBE COLLECTORS

In this design (Figure 2.18) the heat transfer medium is either led via a tube-in-tube system (coaxial tube) to the base of the glass bulb, where it flows back in the return flow and thereby takes up the heat from the highly spectral-selective absorber, or it flows through a U-shaped tube.

Direct flow-through evacuated tube collectors can be oriented towards the south, but they can also be mounted horizontally on a flat roof.


stainless steel cover
(vacuum-sealed tube closure)
highly transparent
glass tube
selective absorber
distance piece
inlet/outlet of heat
transfer medium liquid
getter
glass end piece


stainless steel cover
(vacuum-sealed tube closure)
highly transparent
glass tube
distance piece
selective absorber
inlet/outlet of heat
transfer medium liquid
getter
glass end piece



2.2.4 Collector accessories

Collectors cannot be installed without additional materials. They are:

- for on-roof installation: roof hooks, special bricks, rails, vent tiles
- for in-roof installation: covering frames
- for flat roof or free installation: bracing, counterweights, bearers.

2.2.5 Collector characteristic curves and applications

Figure 2.22 shows typical efficiency curves and areas of application with the same global solar irradiance for the following collector types: swimming pool absorber, glazed flat-plate collector, and evacuated tube collector. At = 0 each collector type is at its highest efficiency (0).

At its maximum temperature – that is, when it has reached its stagnation temperature – the efficiency equals zero.

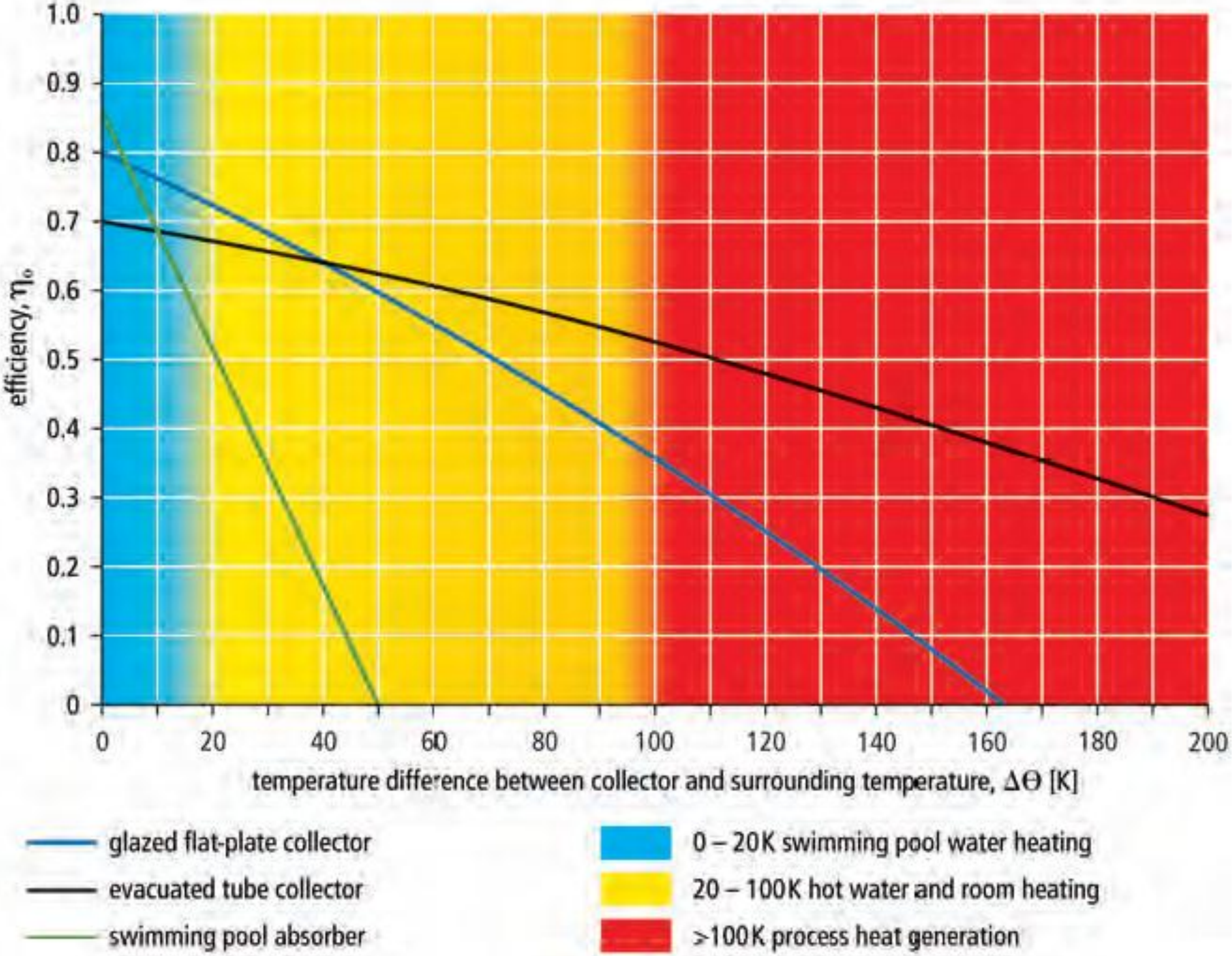
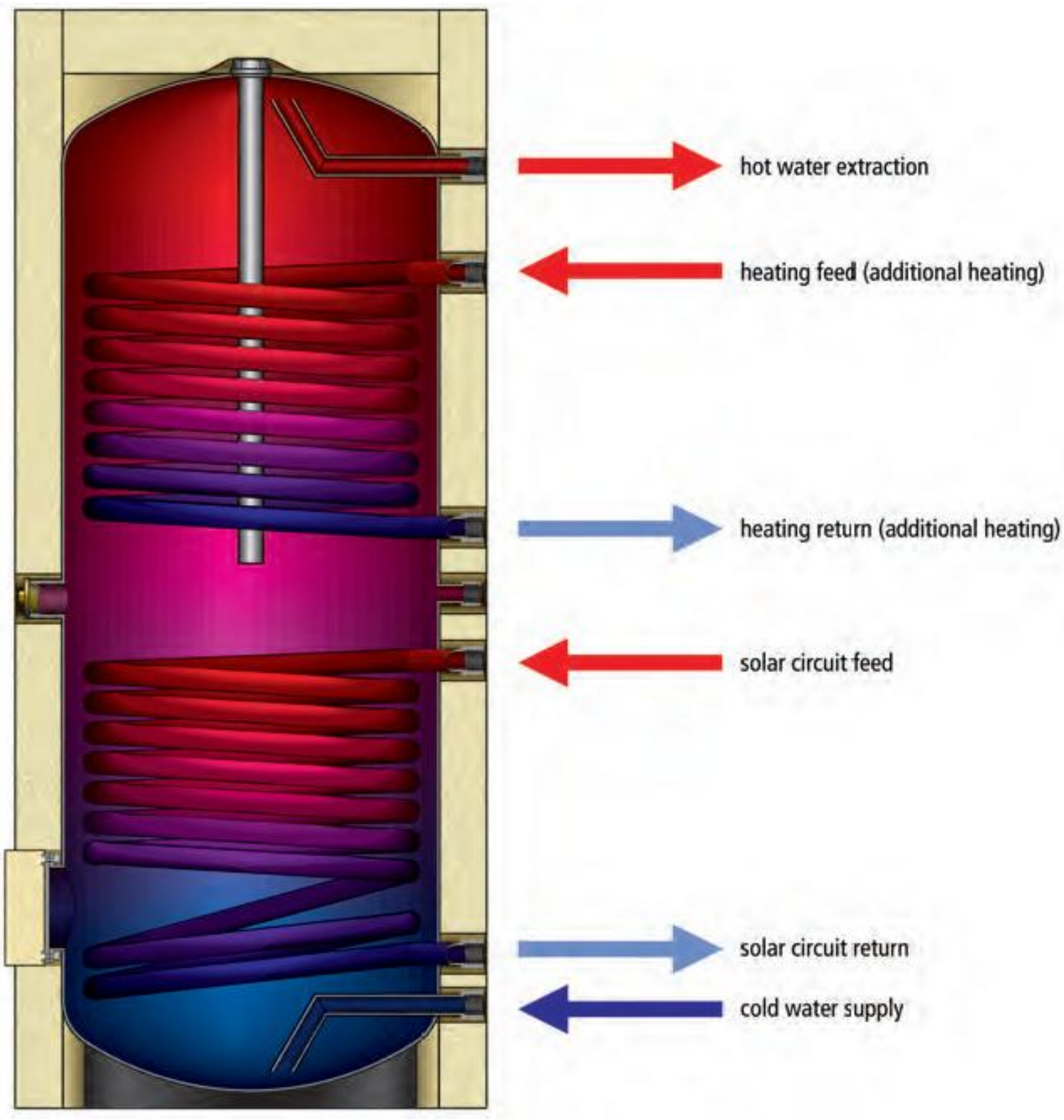


Figure 2.22.
Efficiency characteristic curves for different types of collector and their areas of application (at irradiation of 1000W/m2K)

2.3.2 Domestic hot water stores

Figure 2.24 shows an example of an unvented solar store, as often used in temperate climates. It has the following features:

- two heat exchangers for two heat sources (bivalent): a solar heat exchanger and an additional heat exchanger for a heating boiler
- direct connection to the cold water supply
- pressure tank 4–6 bar (58–87 psi) operating pressure.
  - UK: 150–200 l (39.6–52.8 gallons)
  - Germany: 300–500 l (79.3–132.1 gallons) in the one- and two-family home segment of the market
  - USA: 50–100 gallons (approx 200–400 l)
  - Australia: 300–400 l (79.3–105.7 gallons) for 3–4 persons.



hot water extraction

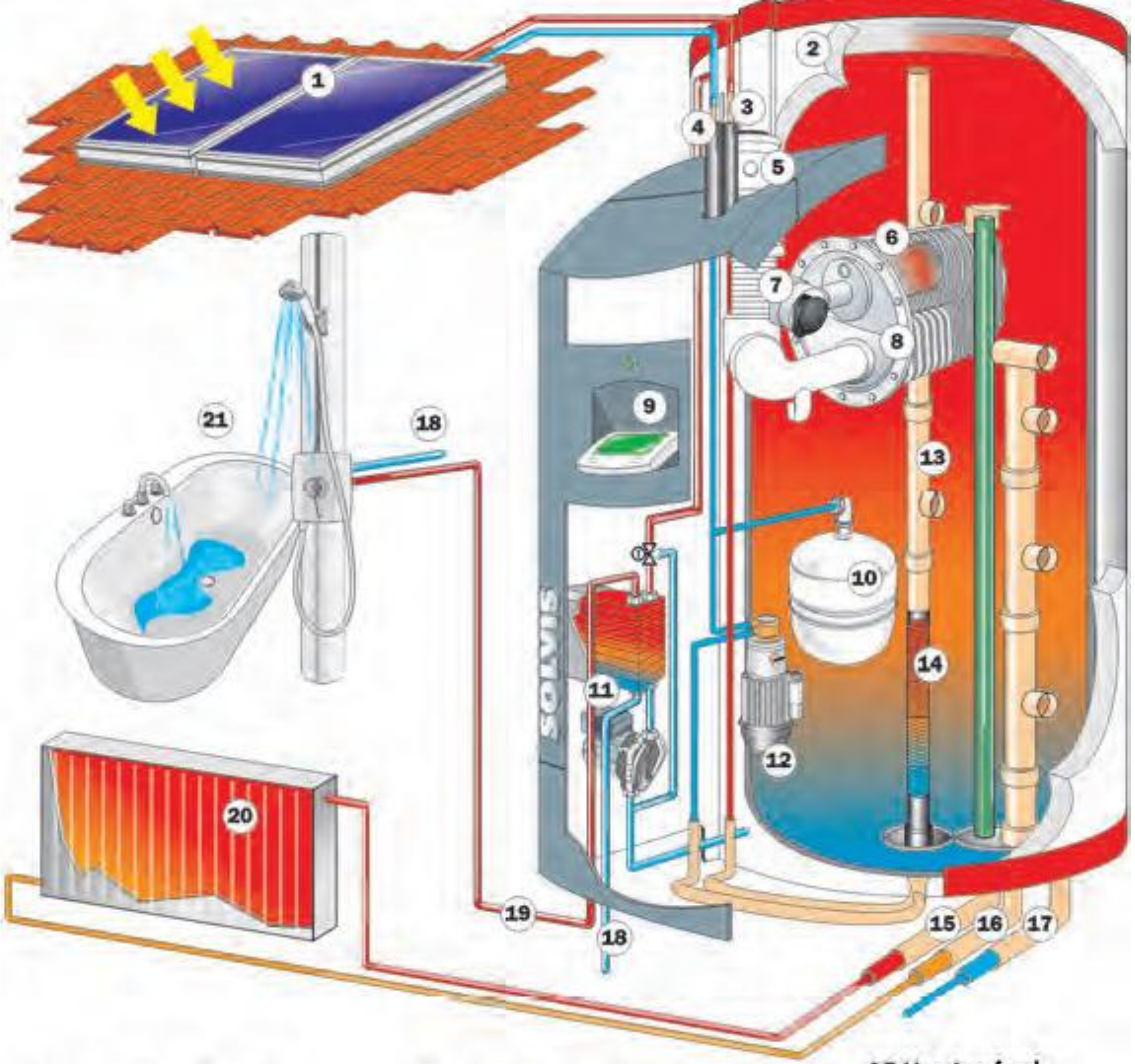
heating feed (additional heating)

heating return (additional heating)

solar circuit feed

solar circuit return

cold water supply



1 Solvis solar collectors
2 Insulation
3 Solar feed
4 Solar return
5 Exhaust pipe connection
6 Gas/oil combustion chamber
7 Gas/oil burner
8 Exhaust heat exchanger
9 System controller SolvisControl 2
10 Solar expansion vessel
11 Hot water station
12 Solar pump
13 Stratified charger
14 Solar heat exchanger
15 Heating feed
16 Heating return
17 Supply and drainage pipe
18 cold water
19 Hot water
20 Heating
21 Hot water outlet

Figure 2.28. Section through the Energy Manager 'SolvisMax' (Manufacturer: Solvis GmbH & Co. KG, Braunschweig)

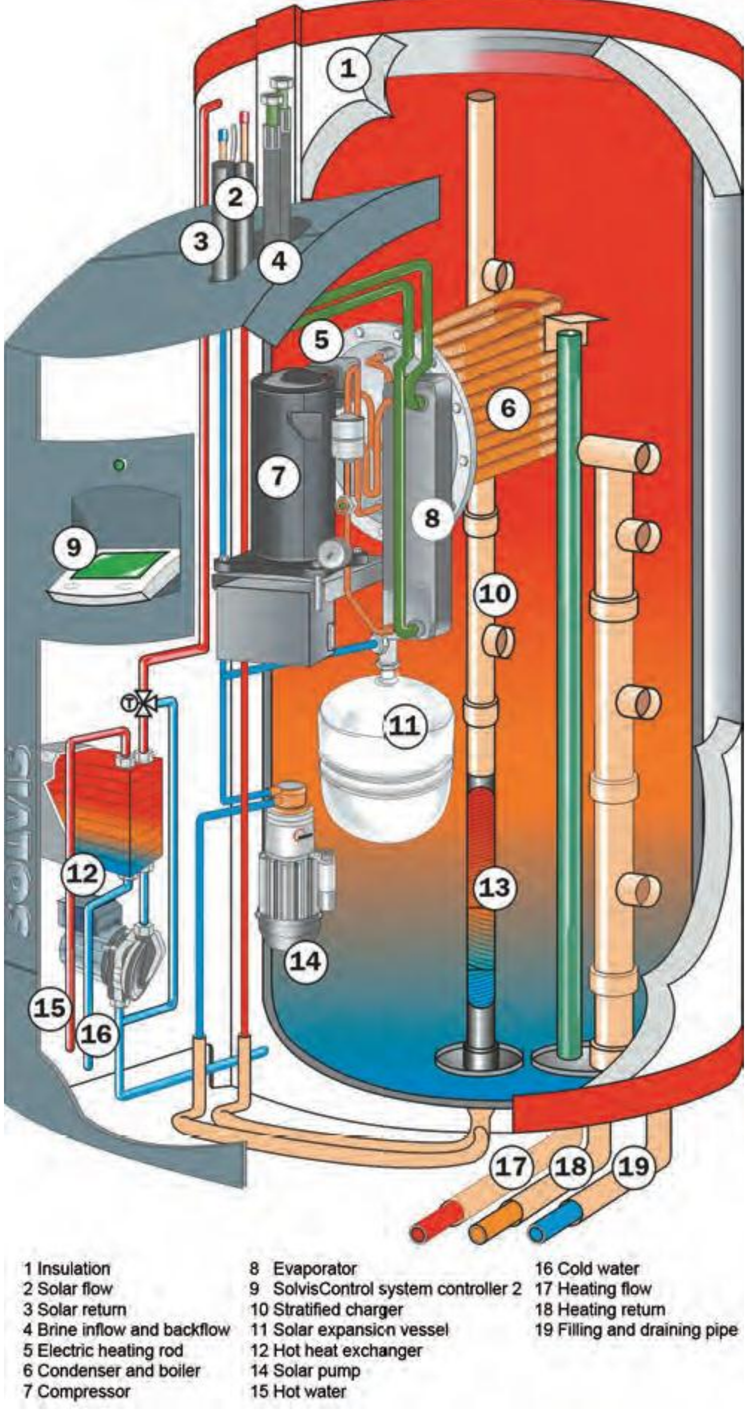


Figure 2.29.
Section through 'SolvisMax' energy manager with heat pump (Manufacturer: Solvis GmbH & Co. KG, Braunschweig)

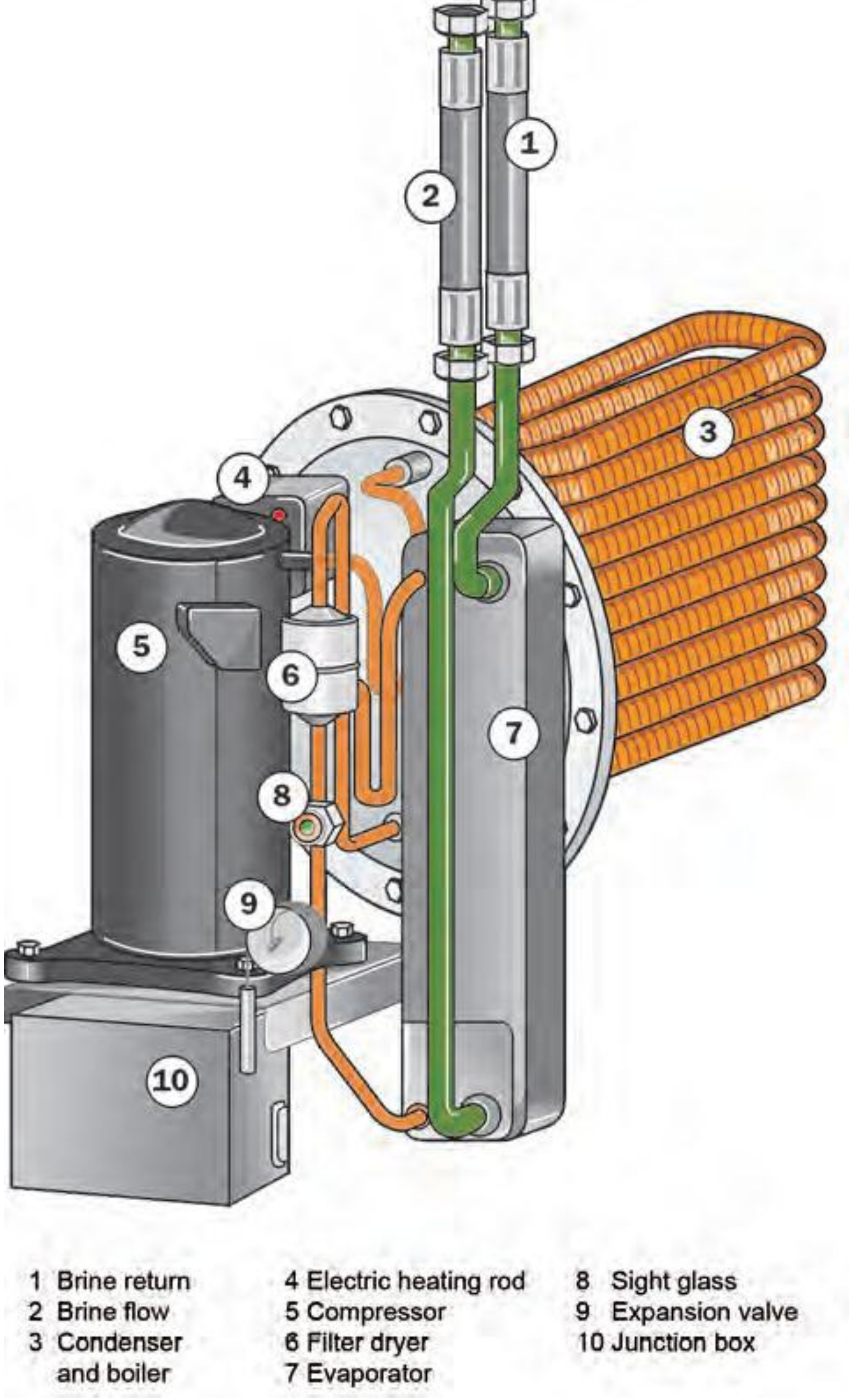


Figure 2.30.
SolvisMax Heat Pump
(Solvis GmbH & Co. KG,
Braunschweig)

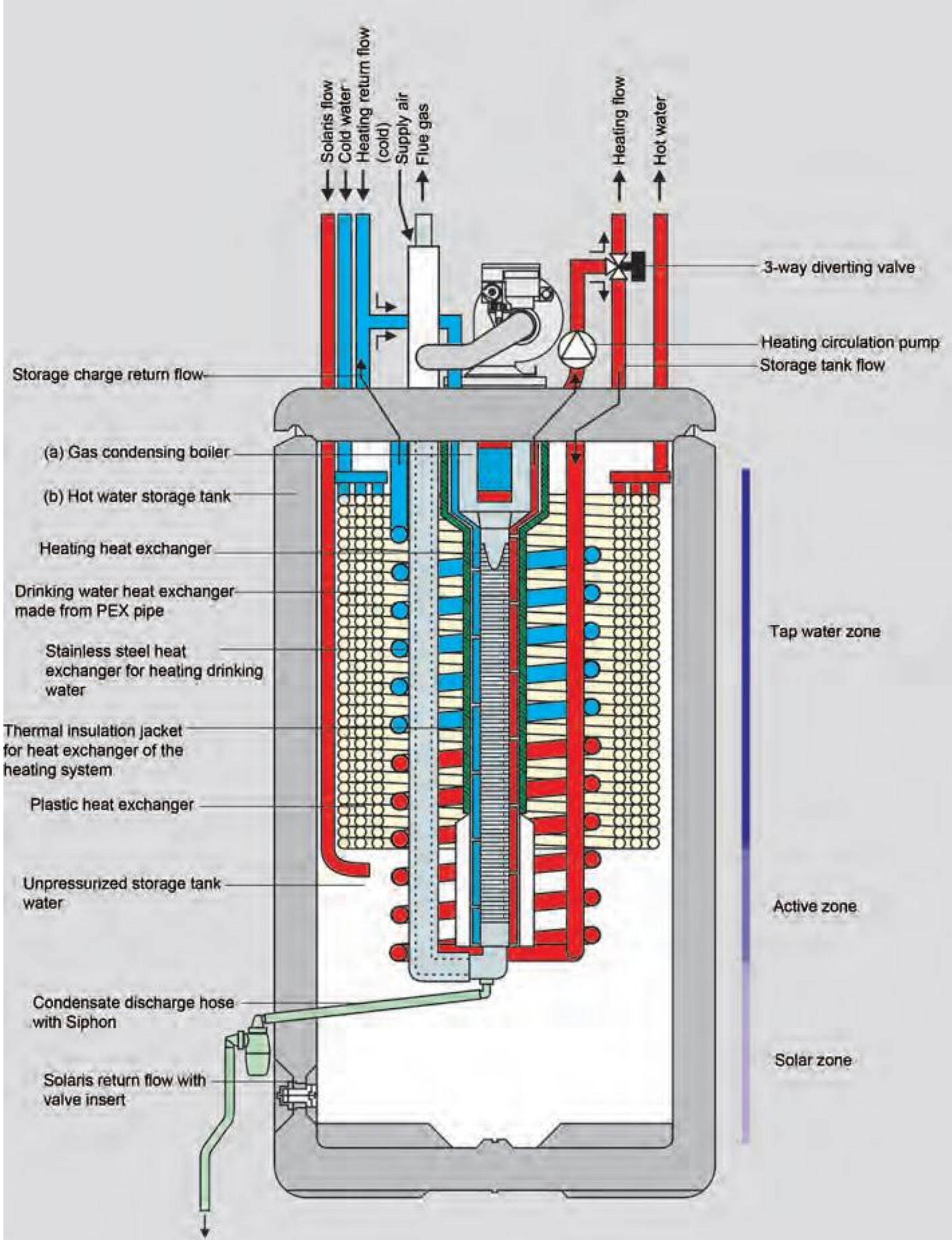


Figure 2.32. GasSolarUnit from Rotex (Manufacturer: Rotex, Gussglingen)

In principle, there are three possibilities to store heat:

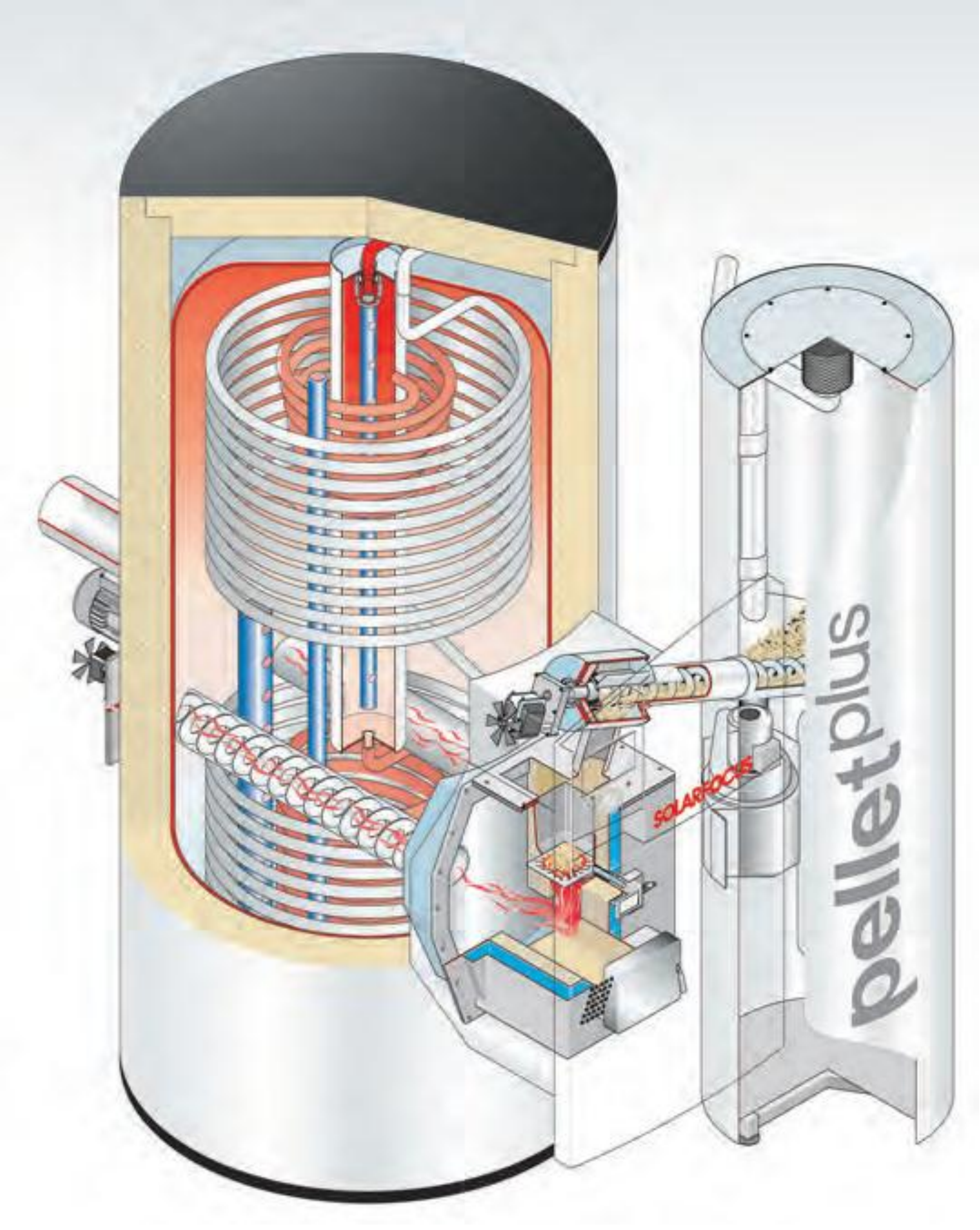
1 Heat storage by means of direct heat supply in insulated, water filled tanks;
2 Latent heat storage, which applies the solid–fluid phase transition of salt hydrates or paraffins;
3 Thermo chemical storage units (sorption tanks) with which supply of heat splits a compound into its properties, and later with the recombination of the components frees that heat again.

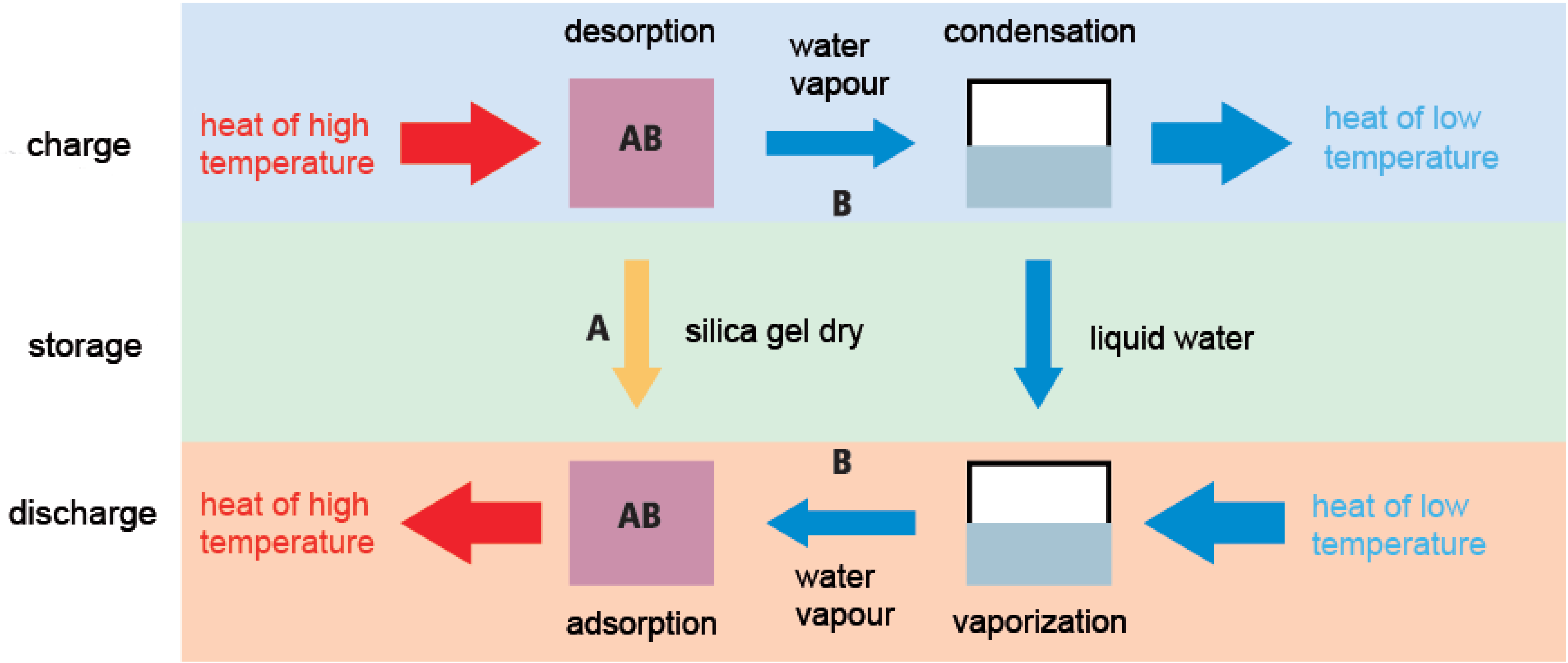
Thermo chemical heat storage differs from the first two storage principles. Heat storage is based on the reversible chemical reaction according to the formula

A + B   AB + Heat

During the load phase, the substance AB is supplied with heat, which dissociates the components A and B. In order to recover the heat, both components A and B are allowed to react with one other. As long as a reaction between A and B is prevented, the heat stored in form of chemical energy cannot be set free. This way, heat can be stored at various temperature levels over a period of time.

In Figure 2.34, A corresponds to dry silica gel, B corresponds to free water vapour and AB to the water saturated silica gel.


SOLARFOCUS
pelletplus



charge

heat of high temperature

desorption

AB

water vapour

B

condensation

heat of low temperature

storage

A

silica gel dry

liquid water

discharge

heat of high temperature

AB

adsorption

B

water vapour

vaporization

heat of low temperature

2.4 Solar circuit

The heat generated in the collector is transported to the solar store by means of the solar circuit. This consists of the following elements:

- the pipelines, which connect the collectors on the roof and the stores
- the solar liquid or transport medium, which transports the heat from the collector to the store
- the solar pump, which circulates the solar liquid in the solar circuit (thermosyphon and ICS systems do not have a pump)
- the solar circuit heat exchanger, which transfers the heat gained to the domestic hot water in the store
- the fittings and equipment for filling, emptying and bleeding
- the safety equipment. The expansion vessel and safety valve protect the system from damage (leakage) by volume expansion or high pressures.

2.4.4 Solar heat exchanger (heat transfer unit)

For the transfer of the heat gained from the sun to the domestic hot water, a heat exchanger (heat transfer unit) is required in twin-circuit systems. We can differentiate between *internal* and *external* heat exchangers.

2.4.4.1 INTERNAL HEAT EXCHANGERS

As internal heat exchangers, *finned tube* and *plain tube* types are available (Figure 2.40). The plain tube heat exchanger possesses a greater heat exchange capacity per square metre of exchanger face. Compared with the finned tube heat exchanger a multiple of the pipe length is required.

Plain tube heat exchangers are installed in the factory, whereas finned tube heat exchangers, because of their more compact design, can be installed into the store on site by means of special flanges and seals.

However, the effectiveness of heat exchangers can be reduced by the build-up of limescale.

Even a layer 2 mm (0.08 inches) thick reduces the heat transfer capacity of a heat exchanger by 20%; a 5 mm (0.2 inch) thickness reduces it by more than 40%.

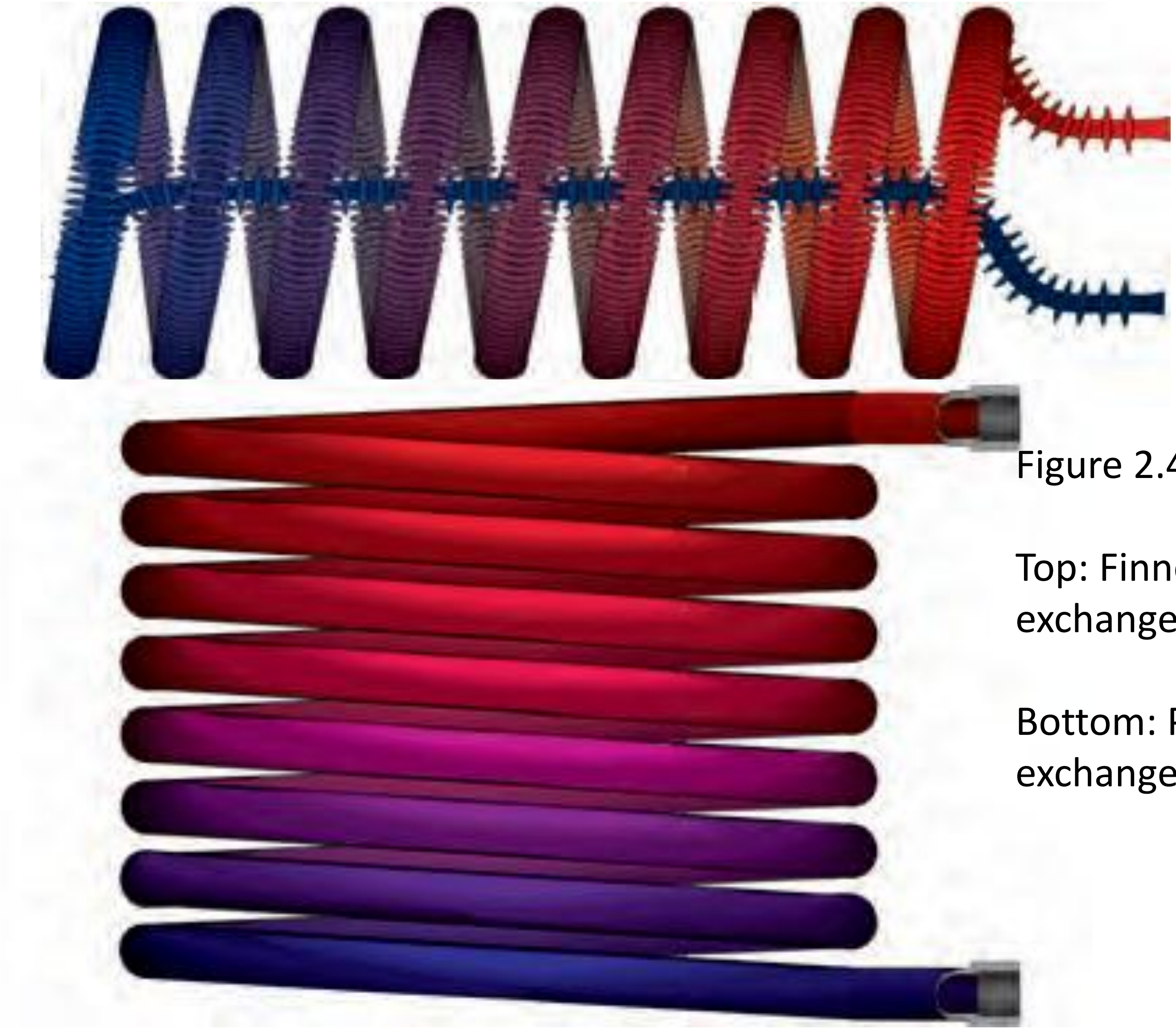


Figure 2.40.

Top: Finned tube heat exchanger

Bottom: Plain tube heat exchanger

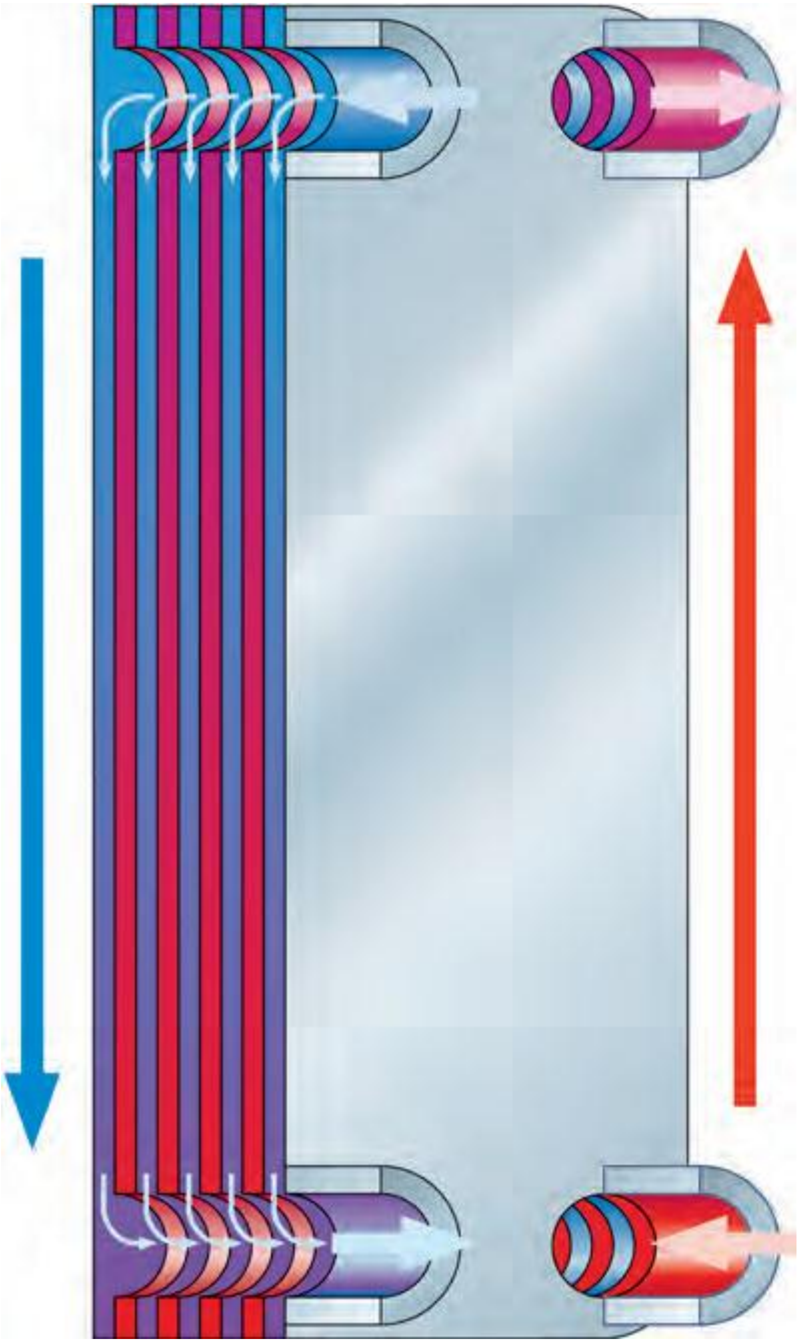


Figure 2.41.
Plate heat exchanger

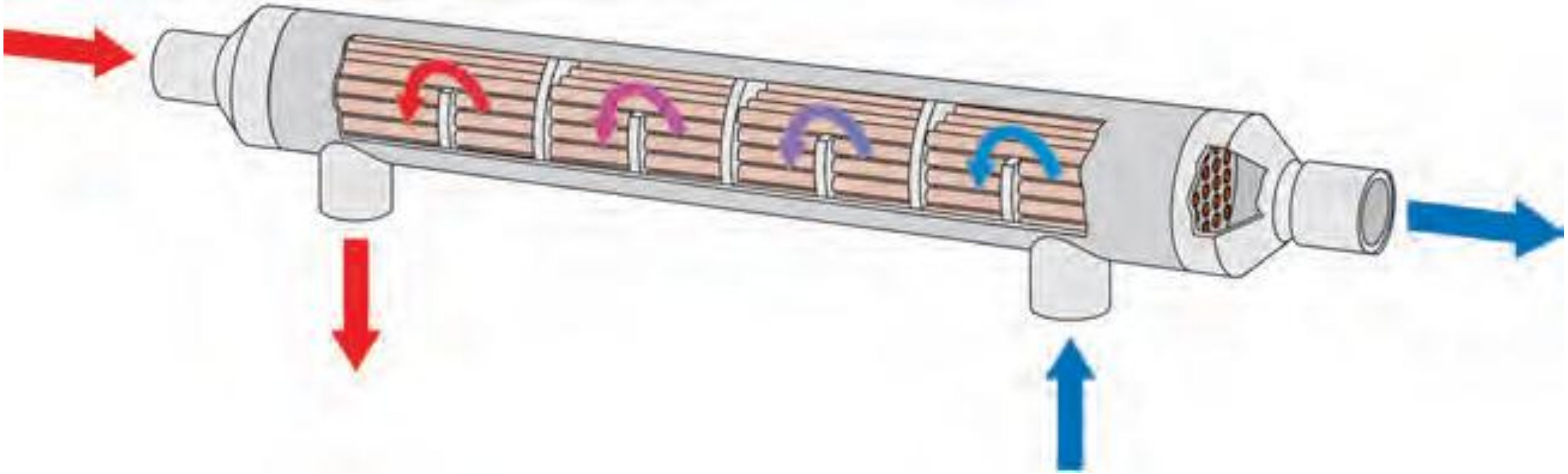


Figure 2.42.
Tubular heat exchanger

2.5.1 Control principles for temperature difference control

Two temperature sensors are required for standard temperature difference control.

One measures the temperature at the hottest part of the solar circuit before the collector output (flow); the other measures the temperature in the store at the height of the solar circuit heat exchanger. The temperature signals from the sensors (resistance values) are compared in a control unit. The pump is switched on via a relay when the switch-on temperature is reached (see Figure 2.50).

The switch-on temperature difference depends on various factors. Standard settings are from 5 K to 8 K. In principle, the longer the pipeline from the collector to the store, the greater the temperature difference that should be set.

The switch-off temperature difference is normally around 3 K. A third sensor can be connected for temperature measurement in the upper area of the store, which permits the draw-off temperature to be read.

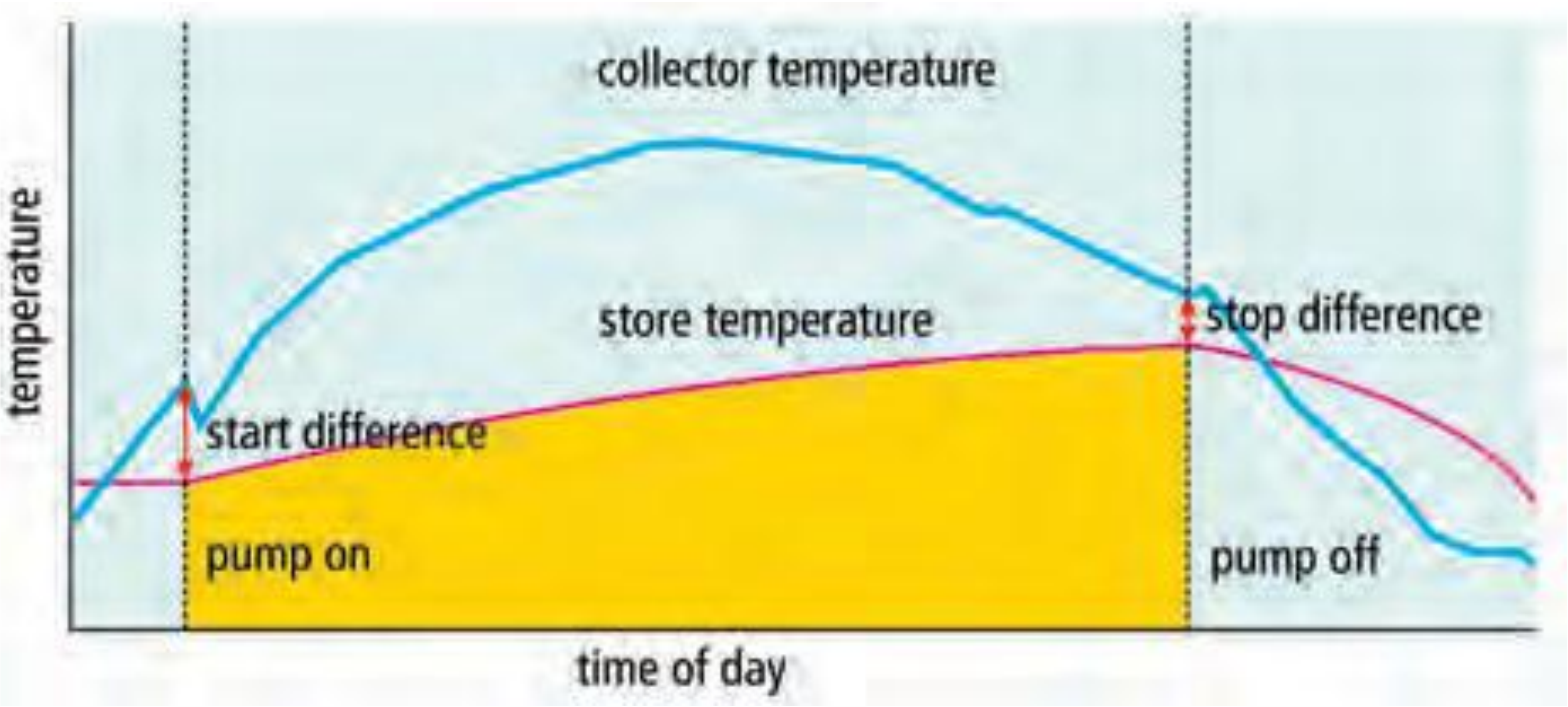


Figure 2.50.

Function of a temperature difference controller shown as the daily progression of the collector and store temperature (schematic)12

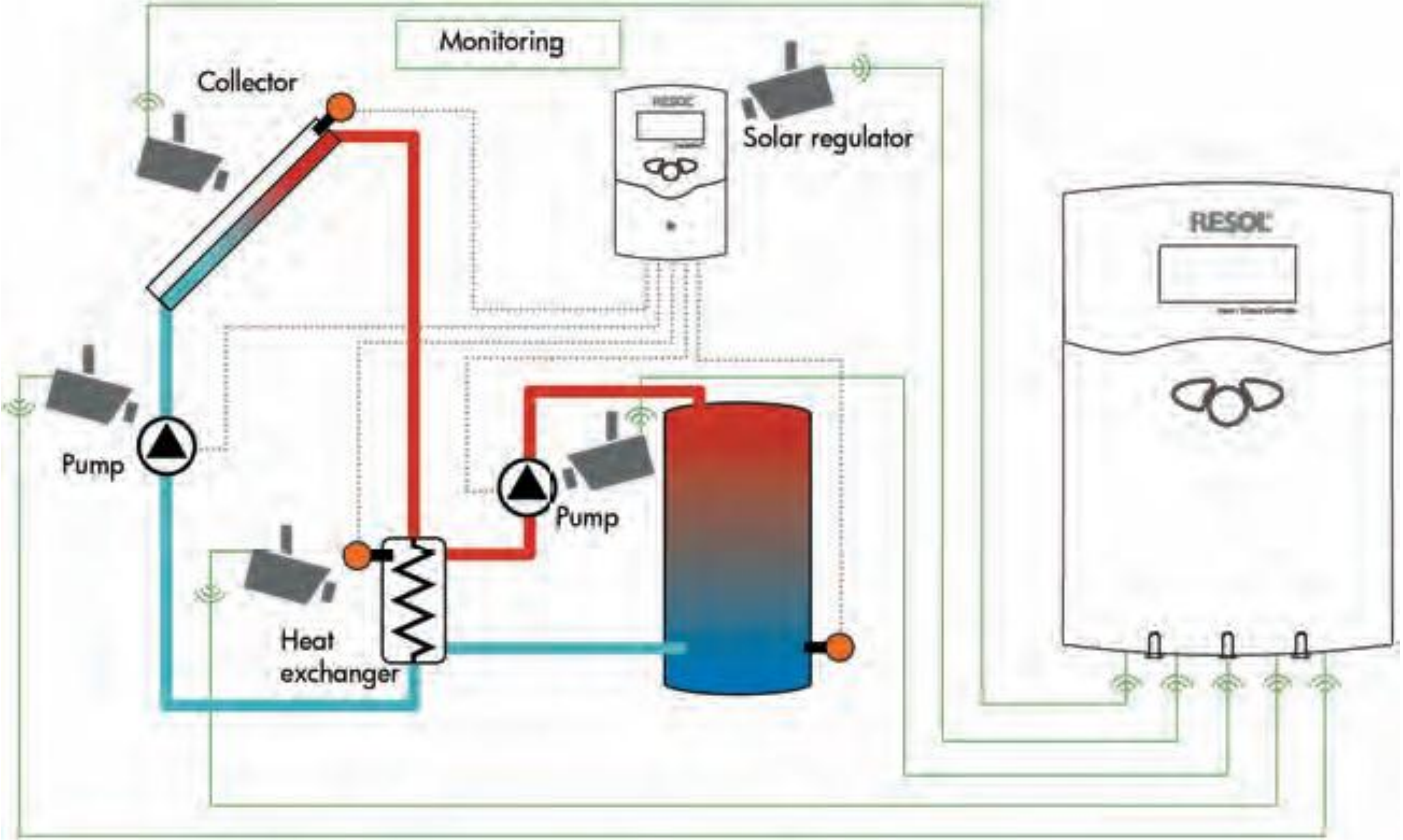


Figure 2.54.
Diagram of the components monitored by IOC
(Manufacturer: RESOL, Hattingen)

6.1 Concentration of solar radiation

Concentration of sunlight for large-scale applications is commonly done with reflecting concentrators; lens systems cannot be used owing to their high price and limitations in size. Instead, a parabolic-shaped reflector concentrates the solar radiation either on a focal line or on a focal point. The concentrator needs to track the sun, so that its incident rays are always perpendicular to the aperture area.

In principle, the main choice is between one-axis and two-axis tracking systems (see Figures 6.1a–6.1c). Systems with one-axis tracking concentrate the sunlight onto an absorber tube in the focal line of the concentrator, whereas two-axis tracked systems focus the rays of the sun onto a round-shaped absorber at the focal point.

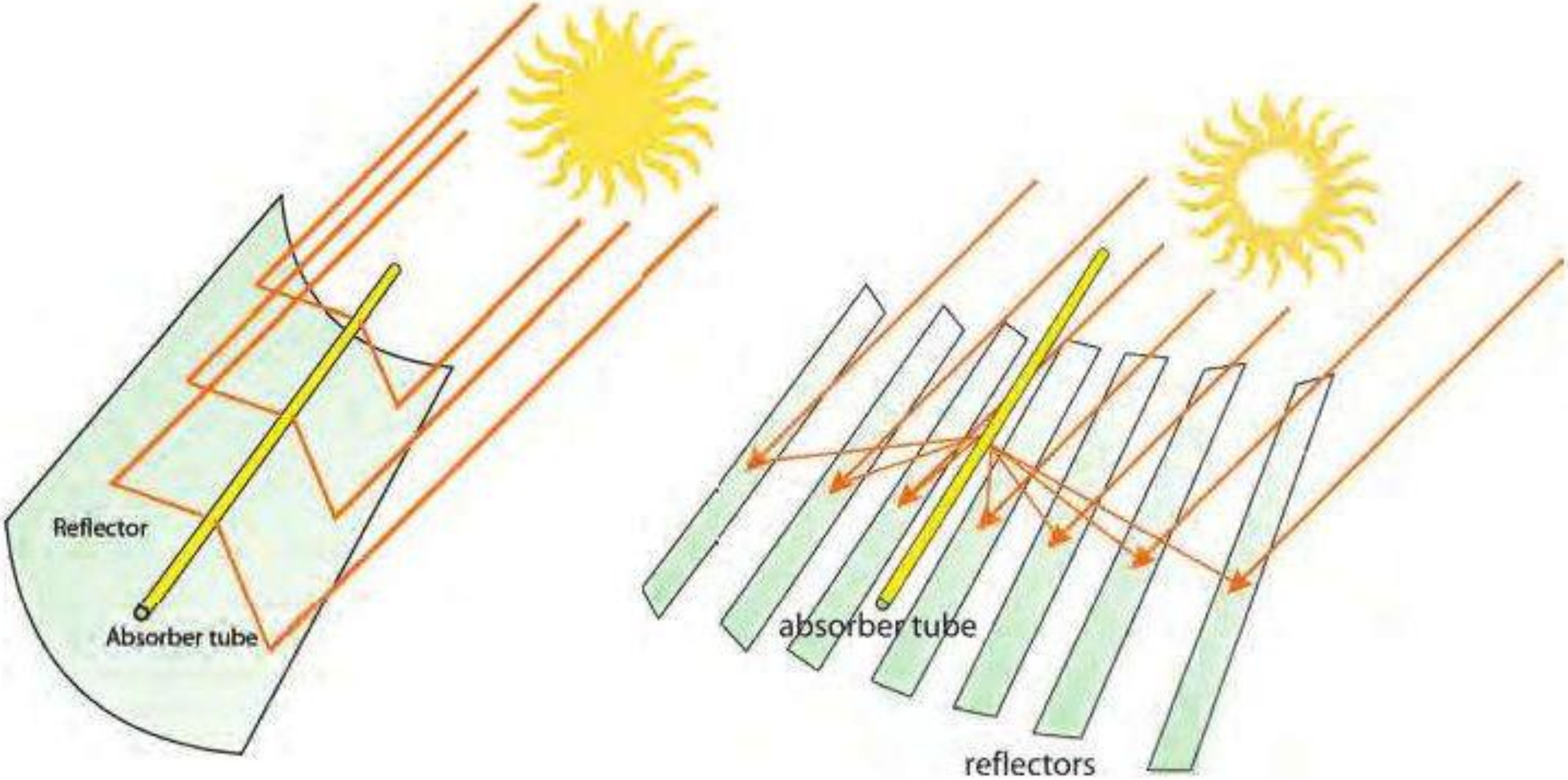
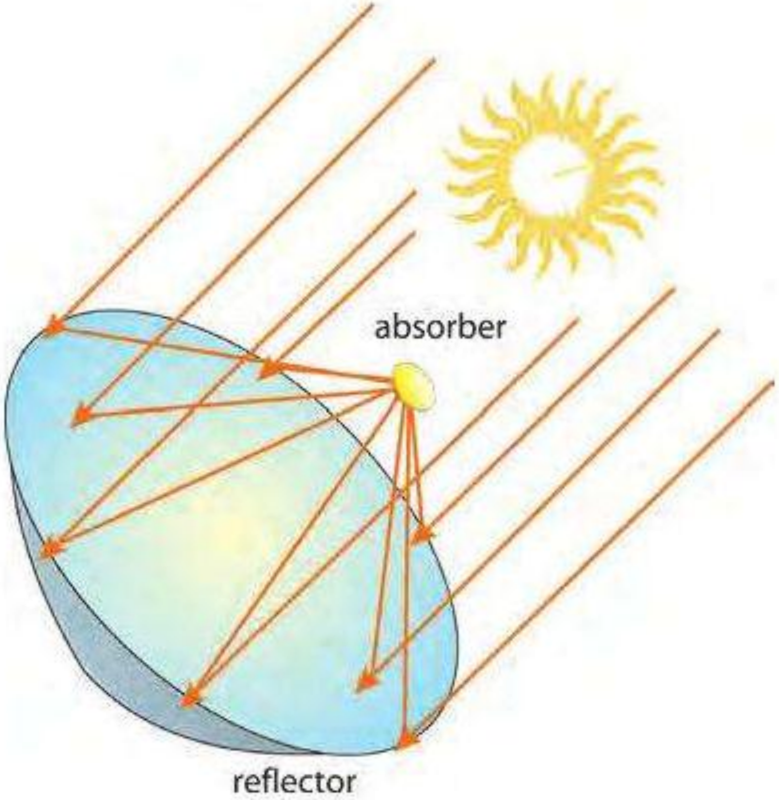

Reflector
Absorber tube
absorber tube
reflectors

Figure 6.1b.
Concentration of solar radiation: single reflector with two-axis tracking



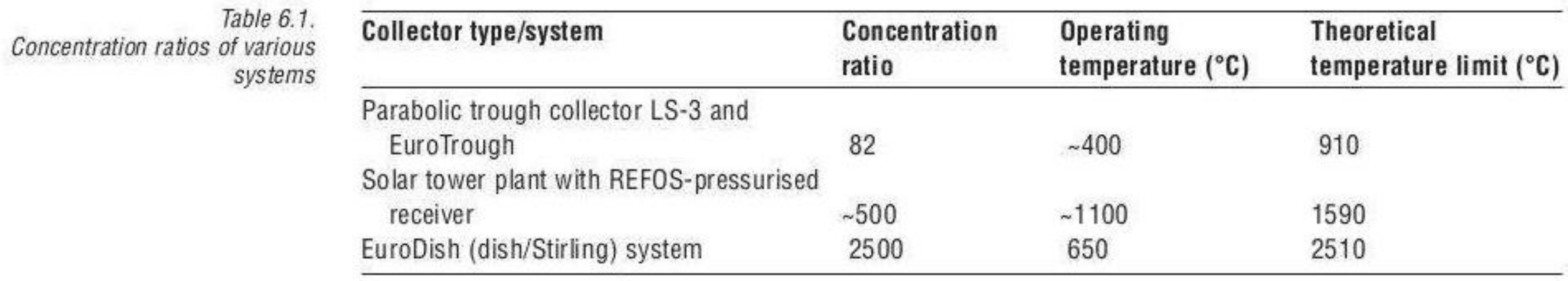
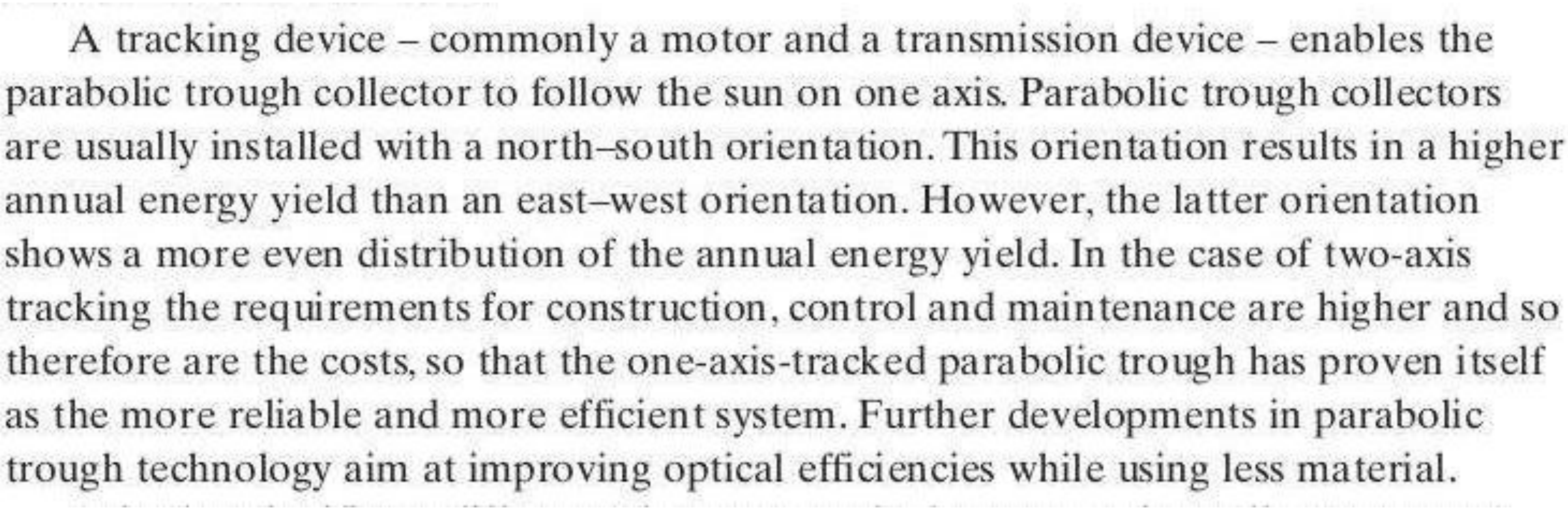


Table 6.1. Concentration ratios of various systems

Collector type/system	Concentration ratio	Operating temperature (°C)	Theoretical temperature limit (°C)
Parabolic trough collector LS-3 and EuroTrough	82	~400	910
Solar tower plant with REFOS-pressurised receiver	~500	~1100	1590
EuroDish (dish/Stirling) system	2500	650	2510



A tracking device – commonly a motor and a transmission device – enables the parabolic trough collector to follow the sun on one axis. Parabolic trough collectors are usually installed with a north–south orientation. This orientation results in a higher annual energy yield than an east–west orientation. However, the latter orientation shows a more even distribution of the annual energy yield. In the case of two-axis tracking the requirements for construction, control and maintenance are higher and so therefore are the costs, so that the one-axis-tracked parabolic trough has proven itself as the more reliable and more efficient system. Further developments in parabolic trough technology aim at improving optical efficiencies while using less material.

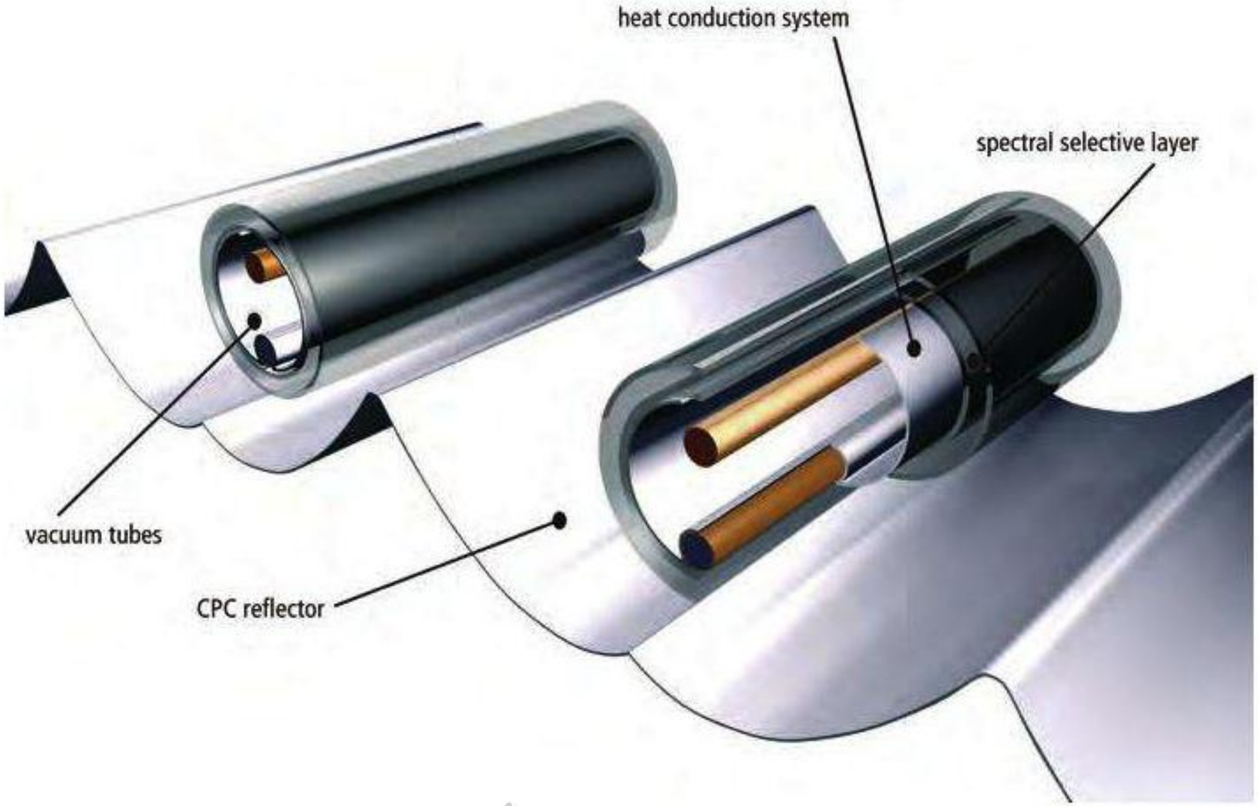


Figure 6.2.
Schematic structure of a CPC tube collector. Source: Consolar

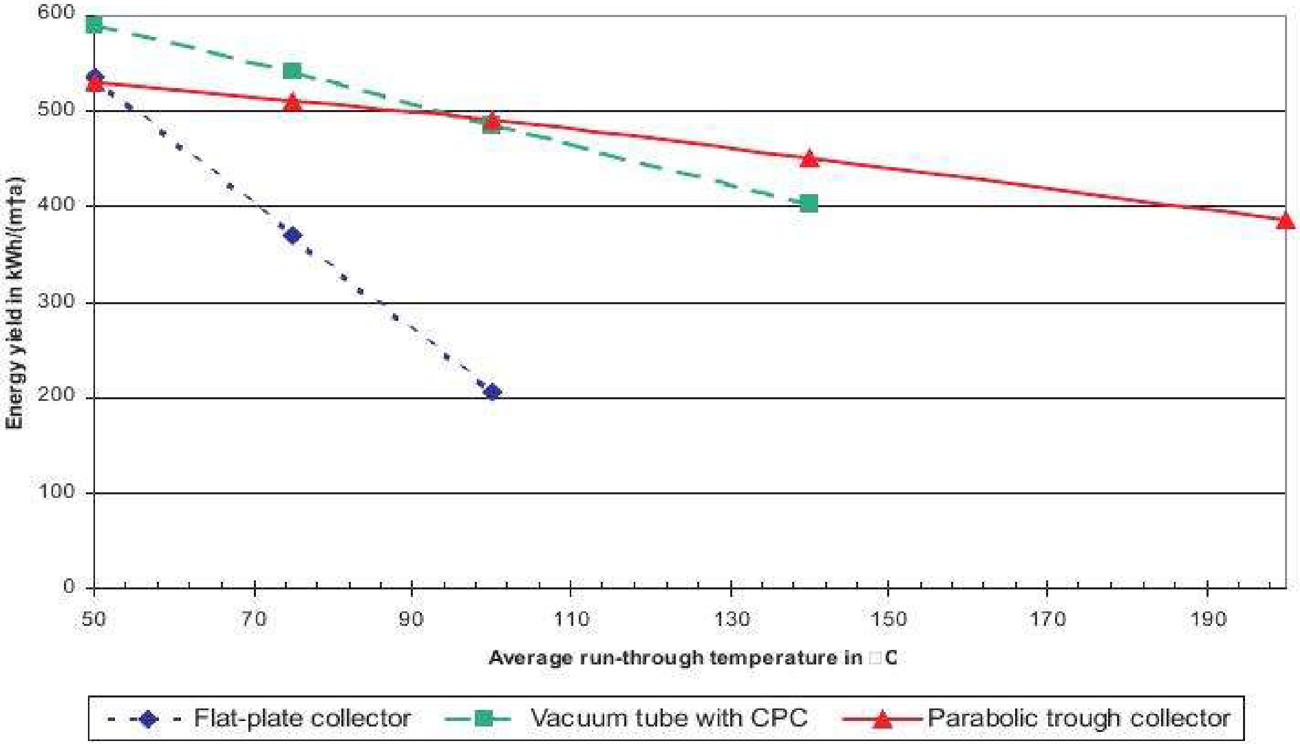


Figure 6.3.
Energy yield against mean flow temperature for various collector types at Würzburg, Germany. Source: Klaus Hennecke

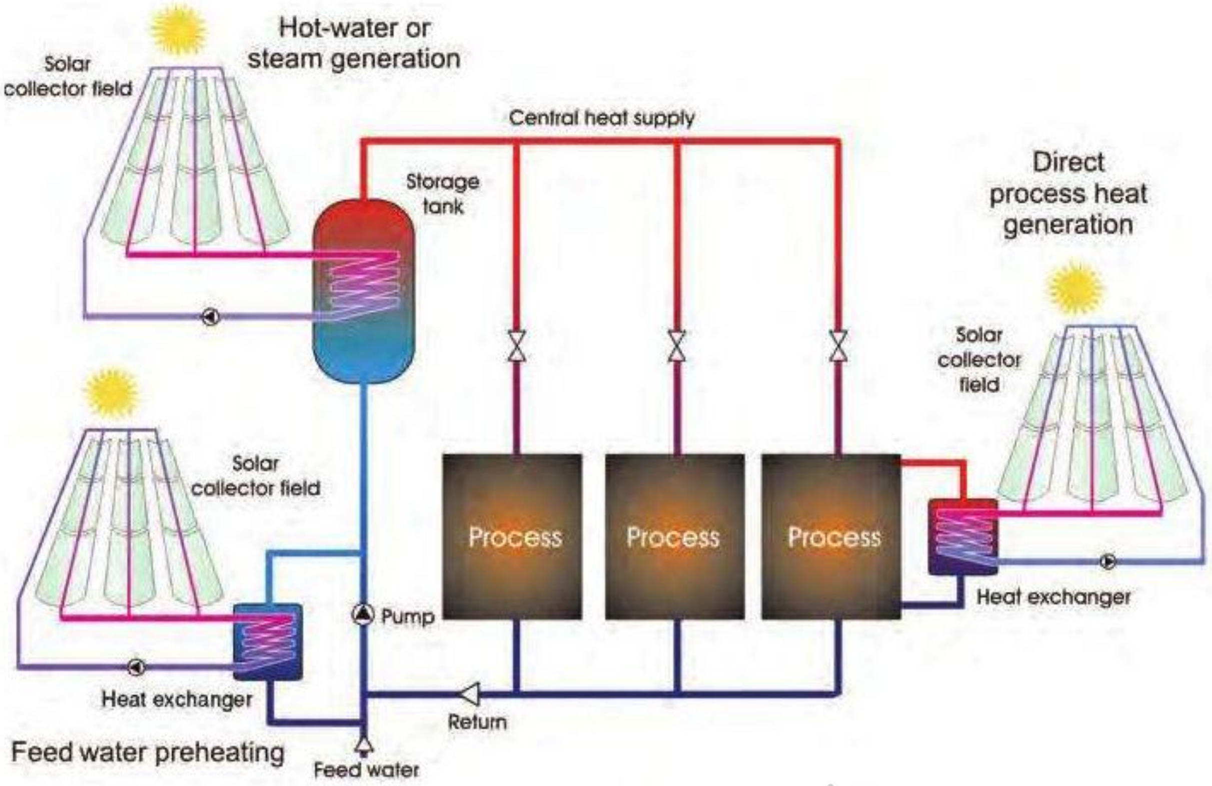
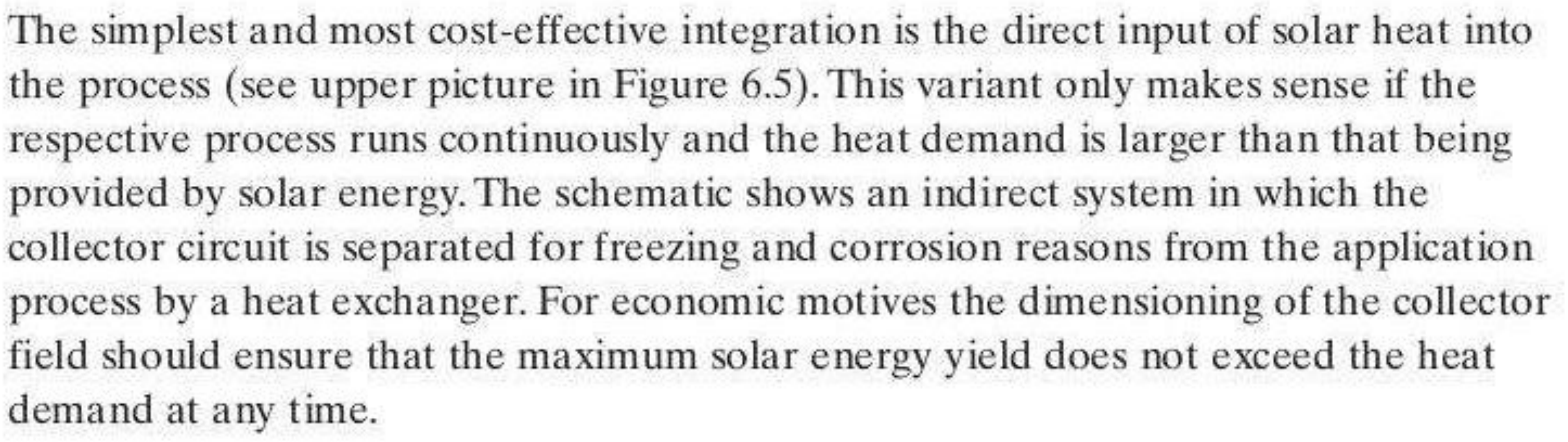


Figure 6.4.
Schematic of various options for integrating solar systems into a conventional heat supply. Source: DLR



The simplest and most cost-effective integration is the direct input of solar heat into the process (see upper picture in Figure 6.5). This variant only makes sense if the respective process runs continuously and the heat demand is larger than that being provided by solar energy. The schematic shows an indirect system in which the collector circuit is separated for freezing and corrosion reasons from the application process by a heat exchanger. For economic motives the dimensioning of the collector field should ensure that the maximum solar energy yield does not exceed the heat demand at any time.

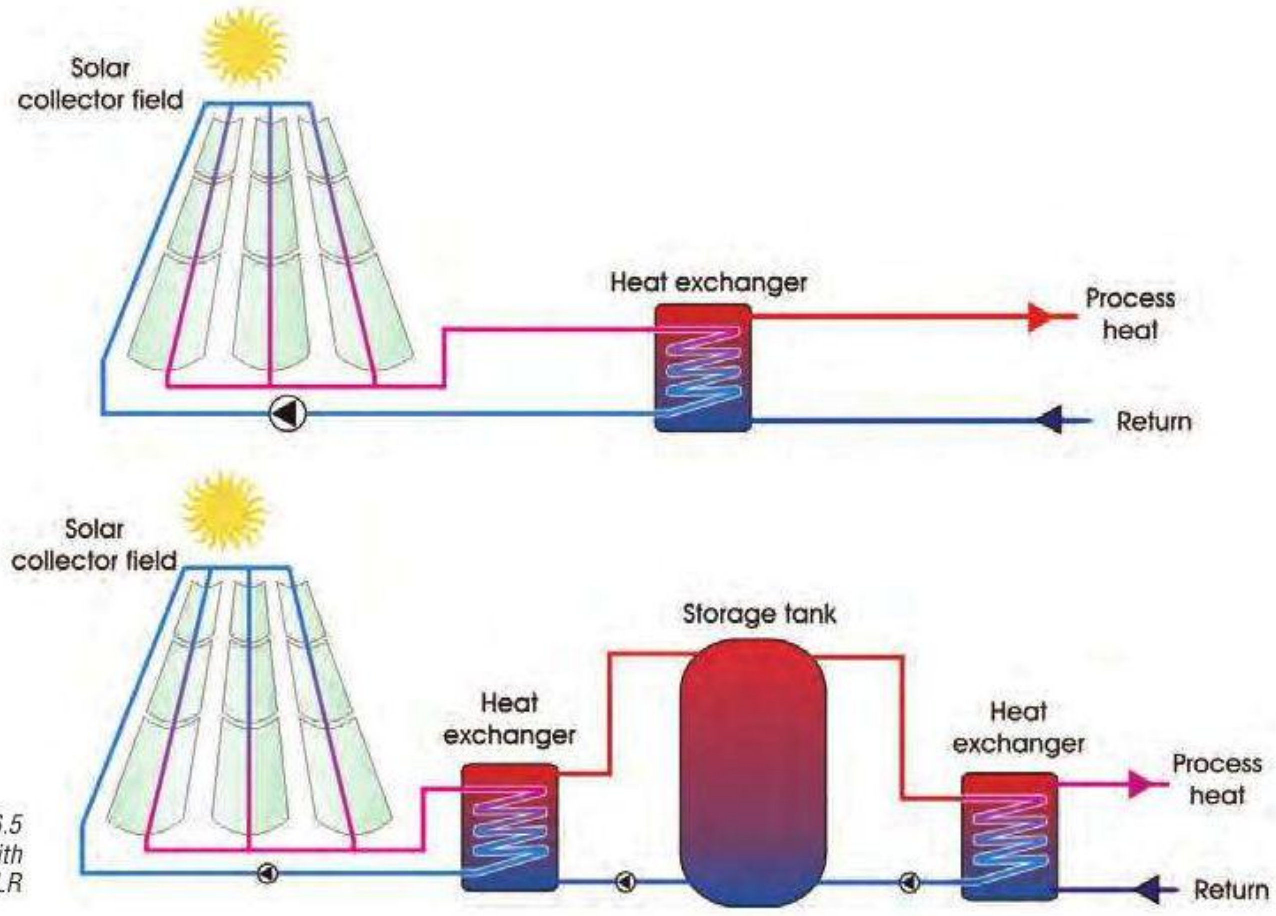
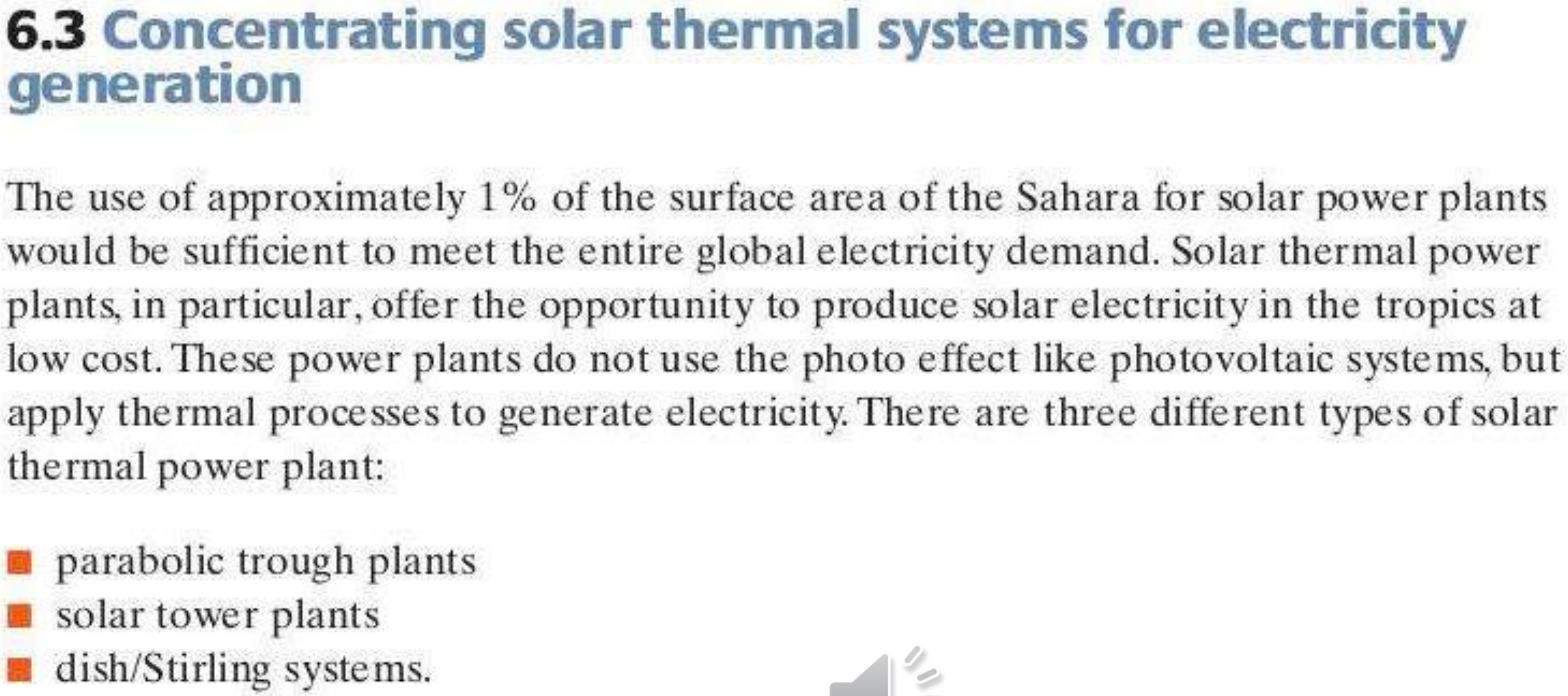


Figure 6.5
Solar system without (above) and with storage (below). Source: DLR



6.3 Concentrating solar thermal systems for electricity generation

The use of approximately 1% of the surface area of the Sahara for solar power plants would be sufficient to meet the entire global electricity demand. Solar thermal power plants, in particular, offer the opportunity to produce solar electricity in the tropics at low cost. These power plants do not use the photo effect like photovoltaic systems, but apply thermal processes to generate electricity. There are three different types of solar thermal power plant:

- parabolic trough plants
- solar tower plants
- dish/Stirling systems.

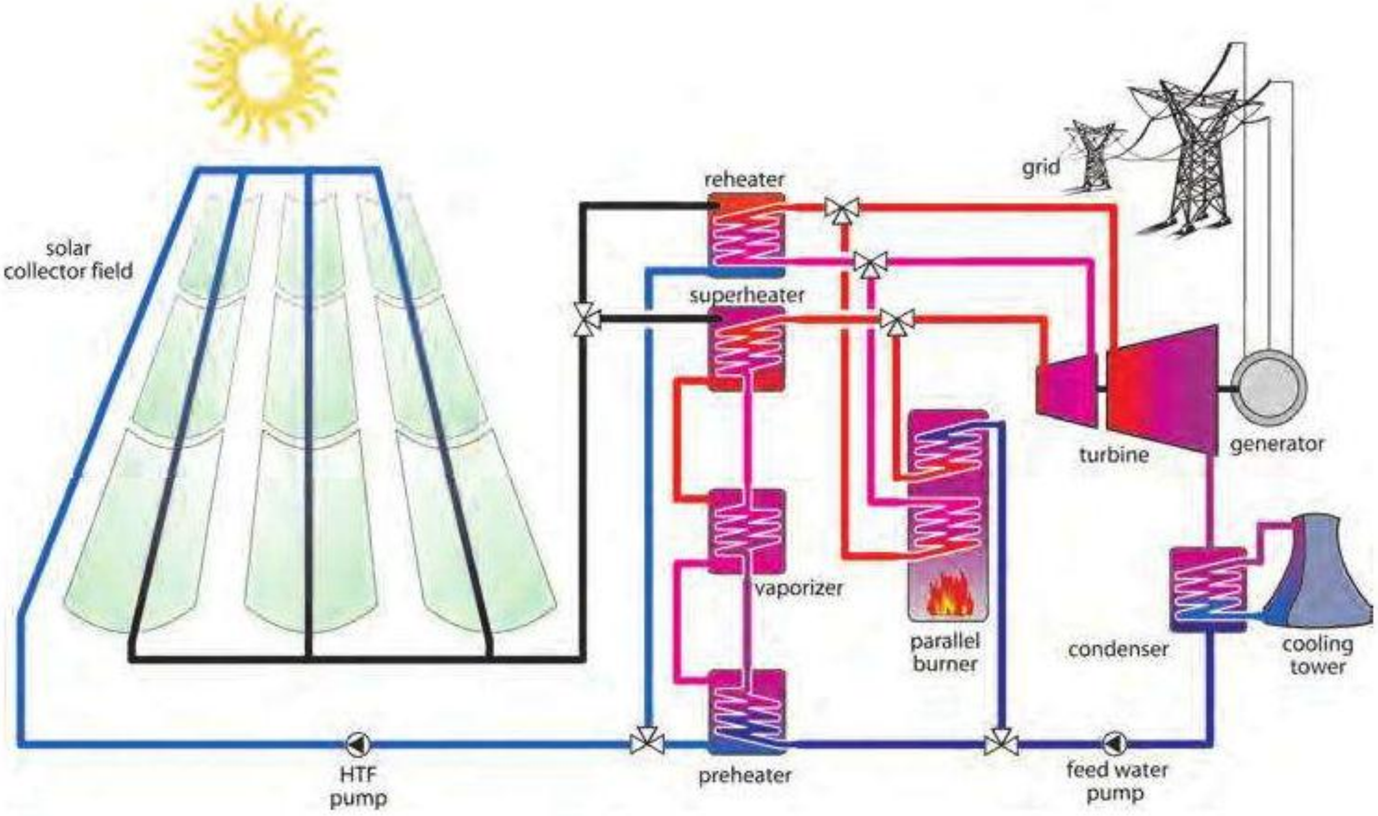


Figure 6.6.
Schematic of an SEGS plant

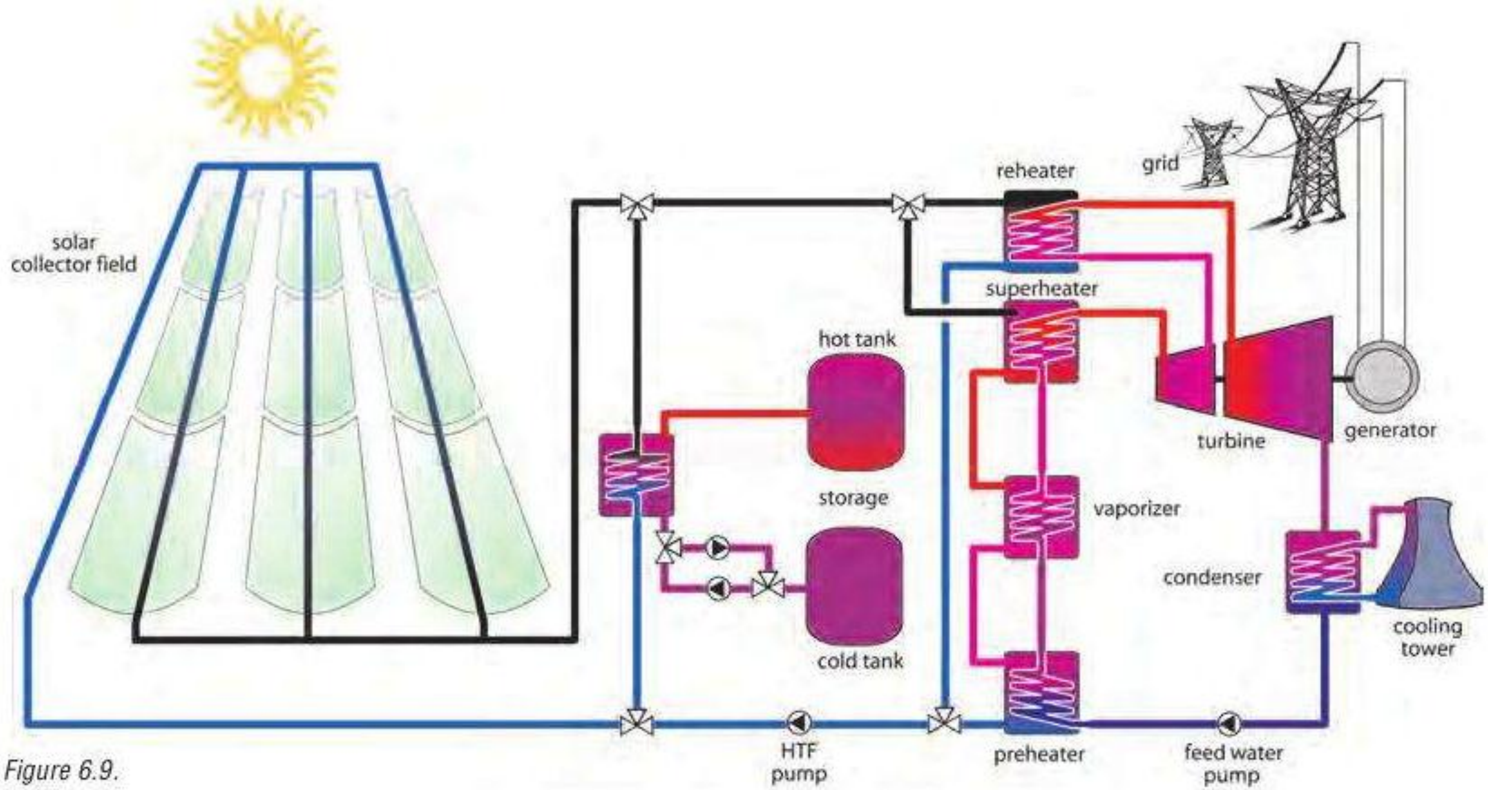


Figure 6.9.
Schematic of a parabolic trough power plant with thermal storage

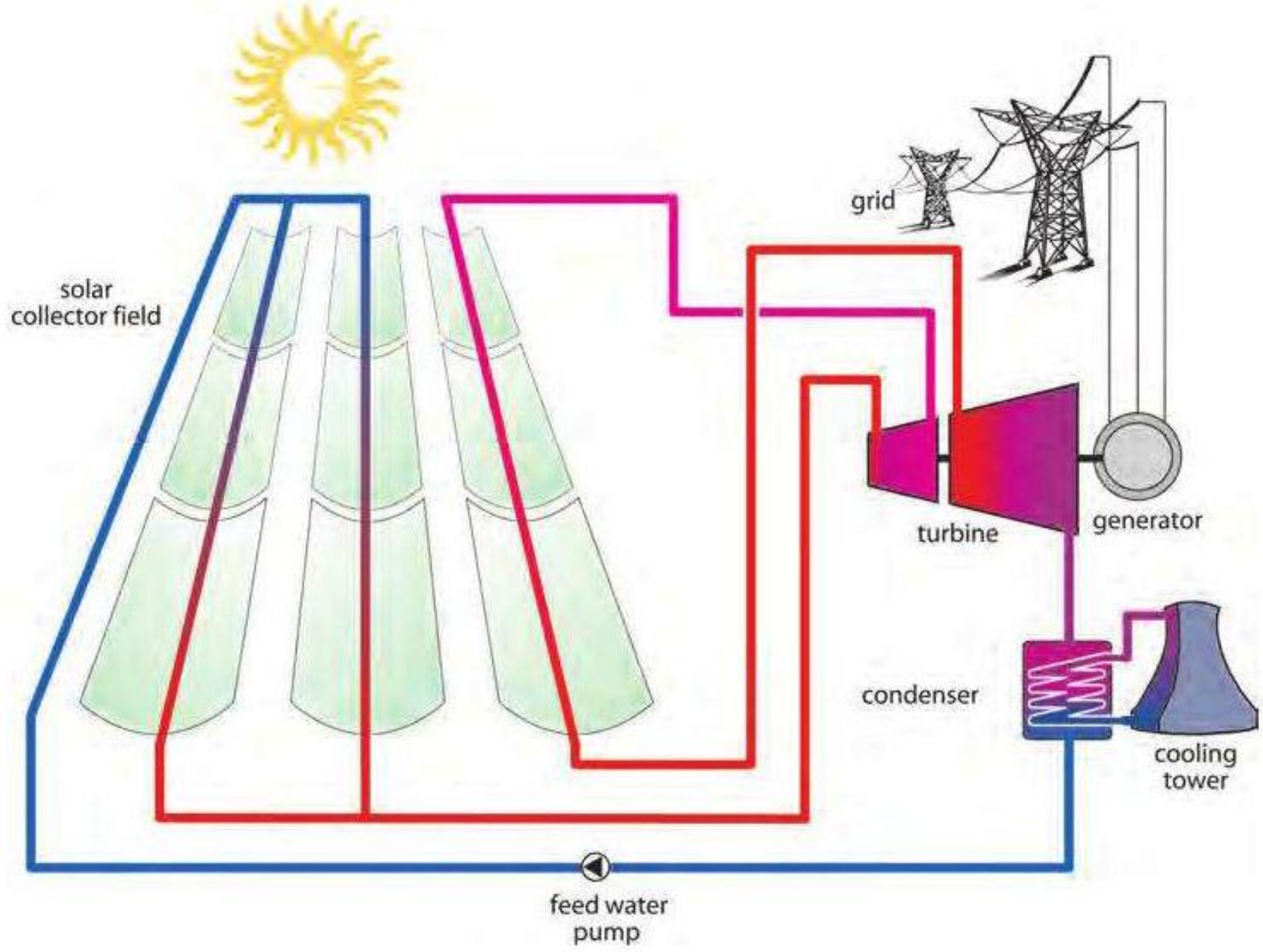


Figure 6.10.
Schematic of a parabolic trough plant with solar thermal direct steam generation

6.3.2 Solar tower plants

Solar tower plants offer another option for producing solar thermal electricity. In this system several hundred, or even several thousand, reflectors are positioned around a central tower. Each of the reflectors, also called a *heliostat* (Figure 6.11), tracks the sun under computer control in order to focus the direct sunlight to the central receiver located at the top of the tower. The accuracy of the tracking is very important to ensure that the sun's reflected rays reach the focal point.

Figure 6.11.
Heliostats. Source: Volker Quaschning

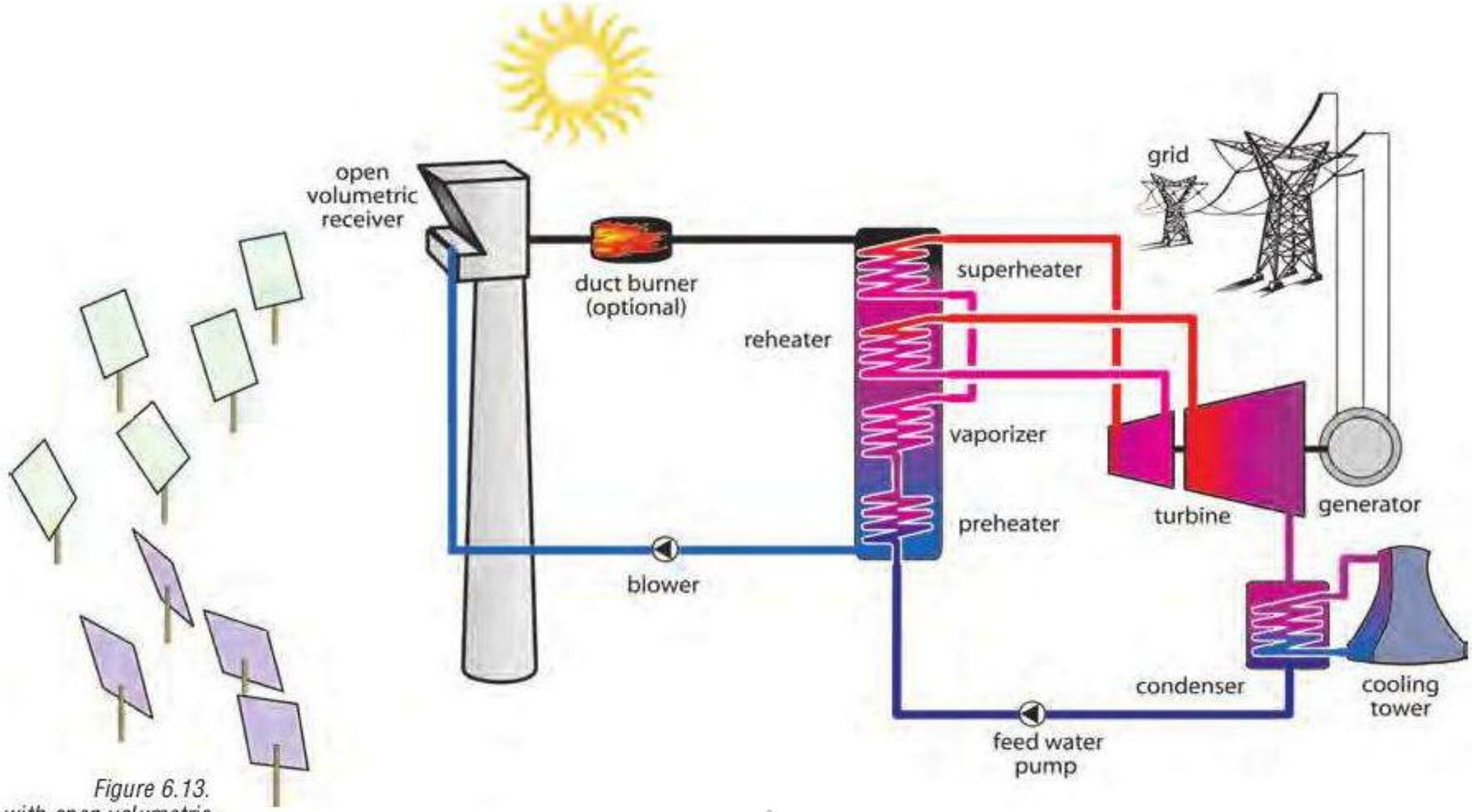


Figure 6.13.
Solar tower plant with open volumetric receiver

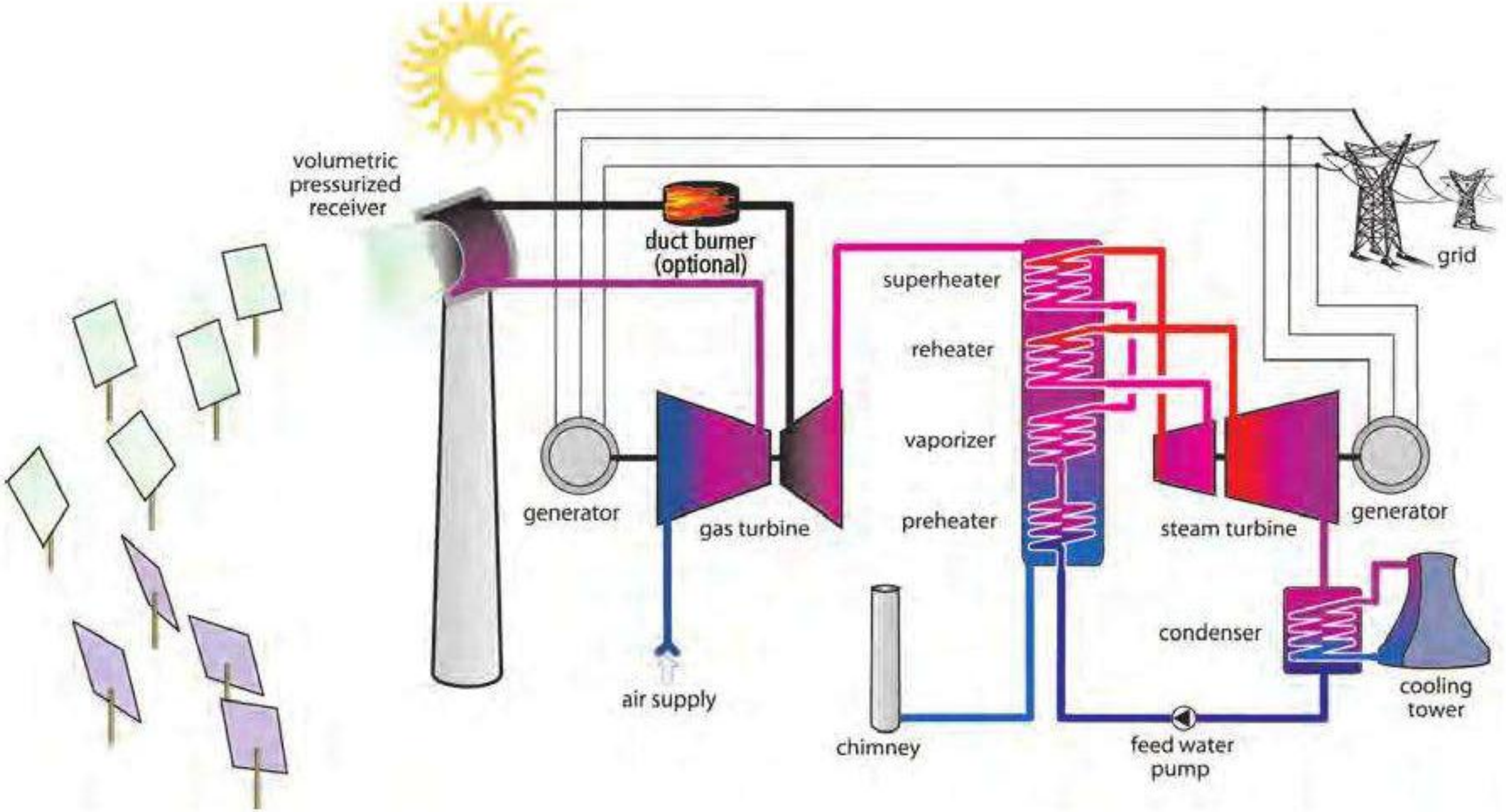
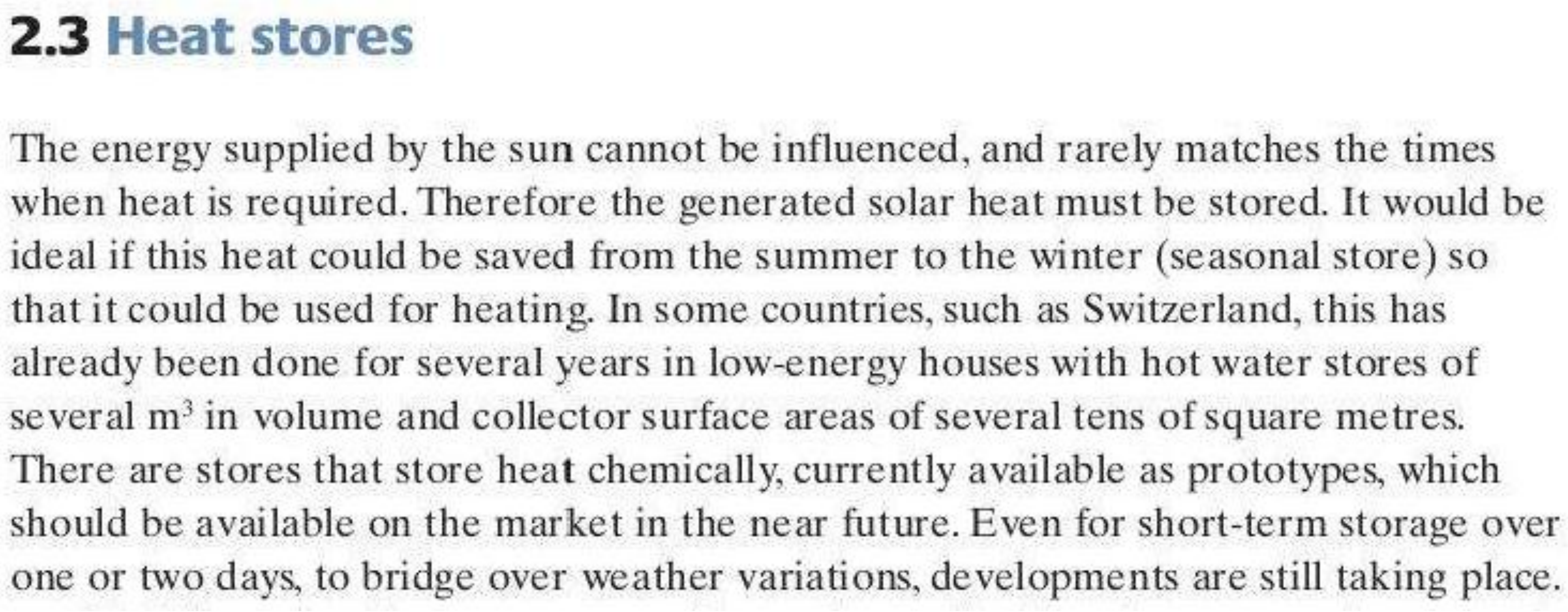


Figure 6.14.
Solar tower plant with a pressurised volumetric receiver for solar operation of gas and steam turbines (REFOS)

While the total capacity still lags behind trough technologies, the numbers are significant and indicate that solar towers offer sufficient benefits to compete on the commercial market.



2.3 Heat stores

The energy supplied by the sun cannot be influenced, and rarely matches the times when heat is required. Therefore the generated solar heat must be stored. It would be ideal if this heat could be saved from the summer to the winter (seasonal store) so that it could be used for heating. In some countries, such as Switzerland, this has already been done for several years in low-energy houses with hot water stores of several m^3 in volume and collector surface areas of several tens of square metres. There are stores that store heat chemically, currently available as prototypes, which should be available on the market in the near future. Even for short-term storage over one or two days, to bridge over weather variations, developments are still taking place.

THE TEMPERATURE AND ENERGY CONTENTS OF A STORE

Let us consider a 300 l solar store in which, after charging and hot water consumption, the temperature layer system shown in Figure 2.25 has built up as a result of its slender construction. The energy content of this tank at a cold water temperature of 15°C is:

$$Q = mc_w\Delta\theta$$

where Q is the heat quantity (Wh), m is the mass (kg), c_w is the specific heat capacity of water = 1.16 Wh/kgK, and $\Delta\theta$ is the temperature difference (K).

$$\begin{aligned} Q &= 100\ \text{kg} \times 1.16\ \text{Wh/kgK} \times 0\ \text{K} + 100\ \text{kg} \times 1.16\ \text{kWh/kgK} \times 15\ \text{K} + 100\ \text{kg} \times 1.16\ \text{Wh/kgK} \times 45\ \text{K} \\ &= 6960\ \text{Wh} \end{aligned}$$

If the same energy content is charged into a store that cannot form layers there will be a uniform mixed temperature of:

$$\begin{aligned} \theta_m &= \frac{6960\ \text{Wh}}{300\ \text{kg} \times 1.16\ \text{Wh/kgK}} + 15^\circ\text{C} \\ &= 35^\circ\text{C} \end{aligned}$$

In this case additional heating is required in the standby area of the store (Figure 2.26); however, in the first instance 100 l of 60°C or 150 l of 45°C water can be drawn off. The calculation of the mixed temperatures is possible using the following equation:

$$\theta_m = \frac{m_1\theta_1 + m_2\theta_2}{m_1 + m_2}$$

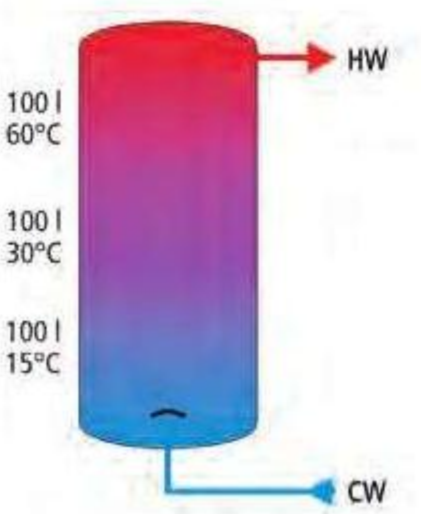


Figure 2.25 (left).
Usable stratification

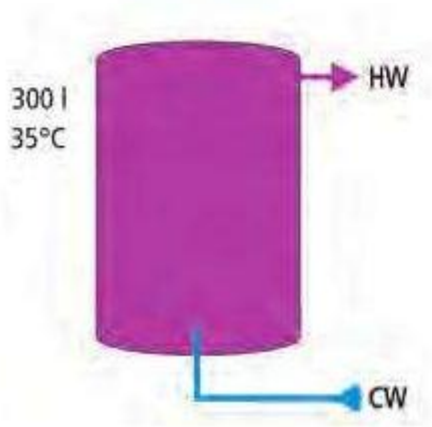


Figure 2.26 (right).
Additional heating required

IRRADIATED POWER, IRRADIANCE, HEAT QUANTITY

When we say that the sun has an irradiance, G, of for example 1000 W/m^2, what is meant here is the capability of radiating a given irradiated power, ϕ (1000 W), onto a receiving surface of 1 m^2 (10.76 ft^2). The watt is the unit in which power can be measured. If this power is referred, as in this case, to a unit area, then it is called the *irradiance*.

1 kW (kilowatt) = 10^3 W (1000 watts)
1 MW (megawatt) = 10^6 W (1 million watts) = 10^3 kW
1 GW (gigawatt) = 10^9 W (1 thousand million watts) = 10^6 kW
1 TW (terawatt) = 10^{12} W (1 million million watts) = 10^9 kW

When the sun shines with this power of 1000 W for 1 hour it has performed 1 kilowatt-hour of work (1 kWh) (Work = Power × Time).

If this energy were converted completely into heat, a heat quantity of 1 kWh would be produced.

Irradiated power,	ϕ (W)
Irradiance,	G (W/m^2)
Heat quantity,	Q (Wh, kWh)

CHARACTERISTIC CURVE EQUATION AND THE THERMAL LOSS COEFFICIENT

The efficiency of a collector can in general be described by:

$$\eta = \frac{\dot{Q}_A}{G}$$

where $\dot{Q}_A$ is the available thermal power (W/m^2), and G is the irradiance incident on the glass pane (W/m^2).

The available thermal power is calculated from the available irradiance at the absorber, converted into heat, minus the thermal losses through convection, conduction and radiation:

$$\dot{Q}_A = G_A - \dot{Q}_L$$

where G_A is the available irradiance (W/m^2), and $\dot{Q}_L$ represents the thermal losses (W/m^2).

The available irradiance is obtained mathematically from the product of: the irradiance hitting the glass pane, G; the degree of transmission of the glass, τ; and the degree of absorption of the absorber, α:

$$G_A = G\tau\alpha$$

The thermal losses are dependent on the temperature difference between the absorber and the air, $\Delta\theta$. To a first approximation (for low absorber temperatures) this relationship is linear, and can be described by the heat loss coefficient, k (W/m^{2}K):

$$\dot{Q}_L = k\Delta\theta$$

If the various values are substituted into the above equation, we obtain for the collector efficiency:

$$\eta = \frac{G\tau\alpha - k\Delta\theta}{G}$$

$$\eta - \frac{k\Delta\theta}{G}$$

At higher absorber temperatures the thermal losses no longer increase linearly with the temperature difference but instead increase more strongly (by the power of 2) as a result of increasing thermal radiation. The characteristic line therefore has some curvature and the equation in a second order approximation is:

$$\eta = \eta_0 - \frac{k_1\Delta\theta}{G} - \frac{k_2\Delta\theta^2}{G}$$

where k_1 is the linear heat loss coefficient (W/m^{2}K), and k_2 is the quadratic heat loss coefficient (W/m^{2}K^2).

In the literature a k_{eff} value is also sometimes given. This is calculated from the k_1 and k_2 values:

$$k_{eff} = k_1 + k_2\Delta\theta$$

when k-values are discussed in the following sections the k_1 value is meant.

3.5.2.3 SYSTEM EFFICIENCY

The system efficiency gives the ratio of solar heat yield to the global solar irradiance on the absorber surface with respect to a given period of time, for example one year:

$$\mathrm{SE} = \frac{\dot{Q}_{\mathrm{S}}}{E_{\mathrm{G}}A} \times 100$$

where SE is the system efficiency (%), $\dot{Q}_{\mathrm{S}}$ is the solar heat yield (kWh/a), E_{G} is the total yearly solar irradiance (kWh/m^{2}a), and A is the absorber surface area (m^2).

If the absorber surface area and the irradiance are known, and if the solar heat yield is measured (heat meter), the system efficiency can be determined:

Example:

$A = 6\ \mathrm{m}^2$
$E_{\mathrm{G}} = 1000\ \mathrm{kWh/m^2a}$ (central Europe)
$\dot{Q}_{\mathrm{s}} = 2100\ \mathrm{kWh/a}$

Then the system efficiency is given by

$$\mathrm{SE} = \frac{2100\ \mathrm{kWh} \times \mathrm{m}^2 \times \mathrm{a}}{1000\ \mathrm{kWh} \times \mathrm{a} \times 6\mathrm{m}^2} \times 100 = 35\%$$

3.5.2.4 STEP 1: DETERMINATION OF HOT WATER CONSUMPTION

The hot water consumption, V_{HW}, of those living in the house is a key variable for system planning, and if it cannot be measured, it should be estimated as closely as possible. When determining the requirements, a check should be made on the possibilities of saving domestic water (for example by the use of water- and energy-saving fittings). A lower water consumption means a smaller solar energy system and hence a lower investment.

However, it is not possible to estimate the hot water consumption of a household accurately, as individual differences are enormous. Of two similar families living in two identical neighbouring houses, one family might use twice as much hot water as the other. For large solar installations, the hot water consumption may be measured separately before designing a solar water heating installation.

During the design of solar energy systems for one- and two-family houses, the following average values can be used for estimating the hot water consumption:[18]

1 × hand washing (40°C; 104°F)	3 l (0.8 gallons)
1 × showering (40°C; 104°F)	35 l (9.3 gallons)
1 × bathing (40°C; 104°F)	120 l (31.7 gallons)
1 × hair washing	9 l (2.4 gallons)
Cleaning	3 l (0.8 gallons) per person per day
Cooking	2 l (0.5 gallons) per person per day
1 × dishwashing (50°C; 122°F)	20 l (5.3 gallons)
1 × washing machine (50°C; 122°F)	30 l (7.9 gallons)

Depending on the fittings in the household, the following average consumption values per person per day can be calculated (usage temperature of hot water approximately 45°C; 113°F):

■ low consumption	20–30 l (5–8 gallons)
■ average consumption	30–50 l (8–13 gallons)
■ high consumption	50–70 l (13–18 gallons)

In the following, all the components for a thermal solar energy system for heating the domestic water for a four-person household in the UK will be dimensioned: collector surface area, domestic water store volume, solar circuit pipework, heat exchanger, circulating pump, expansion vessel and safety valve.

We assume an average hot water consumption of 50 l (13 gallons) per person per day (45°C; 113°F), and a requirement to supply the dishwasher and the washing machine with solar-heated water (either special machines or by using an adapter; see Chapter 2 section 2.3.6 on this subject). According to the information from the user the dishwasher and washing machine operate on average twice per week.*

Taking into account the different hot water temperatures, the daily hot water consumption is then calculated as follows:

$$V_{\mathrm{HW}} = 4 \text{ persons} \times 50\,\mathrm{l}\,(45°\mathrm{C}) + 16\,\mathrm{l}\,(45°\mathrm{C}) = 216\,\mathrm{l}\,(45°\mathrm{C}) \text{ per day}$$

3.5.2.5 STEP 2: HOT WATER HEAT REQUIREMENT

The heat requirement, Q_{HW}, can be determined from the hot water consumption according to the following equation:

$$Q_{\mathrm{HW}} = V_{\mathrm{HW}} c_{\mathrm{W}} \Delta\theta$$

where V_{HW} is the average hot water quantity (l or kg), c_{W} is the specific heat capacity of water (= 1.16 Wh/kgK), and $\Delta\theta$ is the temperature difference between hot and cold water (K).

In our example the necessary daily heat requirement for heating 216 l of water from 10°C (we assume this to be the cold water temperature for this example) to 45°C is given by:

$$\begin{aligned} Q_{\mathrm{HW}} &= 216\ \mathrm{kg} \times 1.16\ \mathrm{Wh/kg\ K} \times (45 - 10)\ \mathrm{K} \\ &= 8770\ \mathrm{Wh} \\ &= 8.77\ \mathrm{kWh\ per\ day} \end{aligned}$$

Note that, depending on the domestic/drinking water regulations, the actual temperature of the hot water delivered should in some countries be higher, for instance 60°C (140°F). In such cases, the water will be mixed at the tapping point. The hot water supply system will have to deliver a smaller amount of water at the high temperature, which will however have the same energy content. This amount is calculated as follows:

$$V_{\theta 2} = \frac{\theta_1 - \theta_c}{\theta_2 - \theta_c} \times V_{\theta 1}$$

where θ_1 is the old temperature level, θ_2 is the new temperature level, θ_c is the cold water temperature, $V_{\theta 1}$ is the volume of water at the old temperature level, and $V_{\theta 2}$ is the volume of water at the new temperature level.

For example, the amount of water at 60°C (140°F) equivalent to the above-mentioned 216 l (57 gallons) at 45°C (113°F), using a cold water temperature of 10°C (50°F), is calculated as follows:

$$V_{60} = \frac{45 - 10}{60 - 10} \times 216 = 151\ \mathrm{l}$$

HEAT LOSSES IN PIPING AND STORES

The significance of thermal insulation is often underestimated. In the following, estimates are made of the possible thermal losses from the solar circuit, the circulation lines and the solar store.

HEAT LOSSES IN INSULATED PIPES

It is possible to make a relatively good estimate of the losses if we consider only the heat conduction through the thermal insulation.[19]

The heat losses can be formulated as follows:

$$Q_{\text{pipe}} = \frac{2\pi\lambda\Delta\theta}{\ln\left(D_{\text{wd}}/D_{\text{pipe}}\right)} \quad \text{(W/m)}$$

where λ is the thermal conductivity of the insulating material (W/mK), D_{wd} is the outside dimension of the insulated pipe (mm), D_{pipe} is the outside diameter of the pipe (mm), ln is natural logarithm, and $\Delta\theta$ is the difference between the temperature in the pipe, θ_{pipe}, and the ambient air temperature, θ_{air} (K).

Example:

λ = 0.04 W/mK (mineral wool)
D_{wd} = 54 mm
D_{pipe} = 18 mm
$\Delta\theta$ = 30 K

In this way Q_{pipe} is calculated as

$$Q_{pipe} = \frac{2\pi \times 0.04\ \mathrm{W} \times 30\ \mathrm{K}}{\ln\ (54\ \mathrm{mm}/18\mathrm{mm})\mathrm{mK}} = 6.9\ \mathrm{W/m}$$

With a total solar circuit length of 20 m and approximately 2000 operating hours per annum, heat losses of $\dot{Q}_{pipe}$ = 6.9 W/m × 20 m × 2000 h/a = 276 kWh/a. This corresponds to an approximate annual yield for a solar energy plant with 5 m^2 of glazed flat-plate collectors of 15% ($\dot{Q}_S$ = 5 m^2 × 1000 kWh/m^2a × 0.35 = 1750 kWh/a).

If a circulation pipe is installed in the building, additional heat losses or an increased heat requirement will have to be allowed for. With a circulation line of 15 m and a running time for the circulation pumps of 2 h per day the following heat losses can be calculated:

$$\dot{Q}_{circ} = 6.9\ \mathrm{W/m} \times 15\ \mathrm{m} \times 2\ \mathrm{h/day} \approx 76\ \mathrm{kWh/a}$$

Therefore the resulting heat losses Q_G are

$$\dot{Q}_G = \dot{Q}_{pipe} + \dot{Q}_{circ}$$
$$= 276\ \mathrm{kWh/a} + 76\ \mathrm{kWhA}$$
$$= 352\ \mathrm{kWh/a}$$

This corresponds to an annual heat gain for 1 m^2 of glazed flat-plate collector surface area.

HEAT LOSSES FROM NON-INSULATED PIPES

It is also possible to estimate the heat losses for non-insulated pipes. However, as very complicated relationships exist here between convection and heat radiation, a calculation is offered for simplification purposes that uses a very much simplified equation using factors.[19] This is valid only for piping diameters below 100 mm and air temperatures around the pipes of $\theta_A = 20°\text{C}$:

$$\dot{Q}_{\text{pipe}} = D_{\text{pipe}}\,(29.85 + 0.027\,\theta_{\text{pipe}}\sqrt[3]{\theta_{\text{pipe}}})\,\Delta\theta \quad (\text{W/m})$$

The pipe diameter must be inserted here in m.

Example:

$D_{\text{pipe}} = 0.018\ \text{m}$
$\theta_{\text{pipe}} = 50°\text{C}$
$\Delta\theta = 30\ \text{K}$

$$\dot{Q}_R = 0.018\ \text{m}(29.85 + 0.027 \times 50°\text{C}\sqrt[3]{50°\text{C}}) \times 30\text{K} \approx 19\ \text{W/m}$$

Therefore, when the solar circuit is not thermally insulated, heat losses arise that are almost three times higher than those for insulated piping. These heat losses will be comparable to the yield of several square metres of solar collectors, and will greatly reduce the yield of the solar system.

HEAT LOSSES FROM STORES

The heat losses from a solar store increase in proportion to the area of its upper area, A, and the temperature difference between the store and the surroundings, $\Delta\theta$:

$$\dot{Q}_{St} \approx A\Delta\theta$$

With the help of the heat loss coefficient k in W/m²K, the following equation is derived:

$$\dot{Q}_{St} = kA\Delta\theta \text{ (W)}$$

For stores the kA value is normally given in W/K.

Example:

kA value = 1.6 W/K
$\Delta\theta = 30$ K

$$\dot{Q}_{St} = 1.6 \text{ W/K} \times 30 \text{ K} = 48 \text{ W}$$

Over the course of a year this store has heat losses of

$$\dot{Q}_{St} = 48 \text{ W} \times 24 \text{ h/d} \times 365 \text{ days/a} \approx 420 \text{ kWh/a}$$

In the above case the heat losses in the store thereby correspond with the solar gain of about 1.2 m² of collector surface.

3.5.2.6 STEP 3: DESIGN AND DIMENSIONING OF SYSTEM COMPONENTS

There are four different methods:

- rough determination of size with an approximation formula
- detailed calculation of the individual components
- graphical design with nomographs
- computer-aided design with simulation programs.

ROUGH DETERMINATION OF SIZE WITH AN APPROXIMATION FORMULA

COLLECTOR SURFACE AREA

For a system designed for a *temperate climate*, a rough estimate for the essential system components can be made under the following assumptions:

- Average hot water requirement, V_{HW} = 35–65 litres (9.3–17.2 gallons) (45°C; 113°F) per person per day.
- Yearly average solar fraction = approximately 60% (covering almost the complete hot water demand in the summer months).
- Collector at optimal or almost optimal orientation and tilt angle (see section 1.1.3).
- No or little shading.
- Design goal is to cover the load almost completely in the months with high irradiation.

The rule of thumb for such situations is:

1–1.5 m² (10.8–16.2 ft²) of glazed flat-plate collector area per person (E_G = 1000 kWh/m²a)
0.7–1 m² (7.5–10.8 ft²) of evacuated tube collector surface per person (E_G = 1000 kWh/m²a)

In our example this approximation formula leads to a required glazed flat-plate collector surface area of 4–6 m^2 (43–64.6 ft^2).

For different irradiation levels (see Chapter 1), these values may be scaled. For instance, when the irradiance is 1300 kWh/m^2a, the collector area may be 1.3 times smaller.

For a *tropical climate*, the collector area can be estimated under the following assumptions:

- Average hot water requirement, V_{HW} = 35–65 litres (9.3–17.2 gallons) (45°C; 113°F) per person per day.
- Favourable solar irradiance conditions.
- Yearly average solar fraction = approximately 80% (auxiliary heating is necessary only in a few months).
- Collector at optimal or almost optimal orientation and tilt angle (see section 1.1.3).
- No or little shading.

The rule of thumb for such situations is:

0.35–0.6 m^2 (3.8–6.5 ft^2) of glazed flat-plate collector area per person (E_G = 2000 kWh/m^2a)

In our example this approximation formula leads to a required glazed flat-plate collector surface area of 1.4–2.4 m^2.

DOMESTIC WATER STORE VOLUMES AND HEAT EXCHANGERS

In general, in order to bridge over a few sunless days without any auxiliary heating, the store volume should be designed to be 1–2 times the daily hot water consumption. In our example of a consumption of 216 l (57 gallons) per day, this leads to a store volume of 200–400 l (52.8–105.7 gallons). For the dimensioning of internal heat exchangers the following approximation formulae apply:

- Finned tube heat exchanger: 0.35 m^2 exchanger surface area per m^2 of collector surface area.
- Plain tube heat exchanger: 0.20 m^2 exchanger surface area per m^2 of collector surface area.

For our example this means that, in the selection of a store with a built-in plain tube heat exchanger, it should have a surface area of about 0.8–1.2 m^2 (4–6 × 0.2 m^2).

SOLAR CIRCUIT PIPES, CIRCULATING PUMPS AND EXPANSION VESSEL

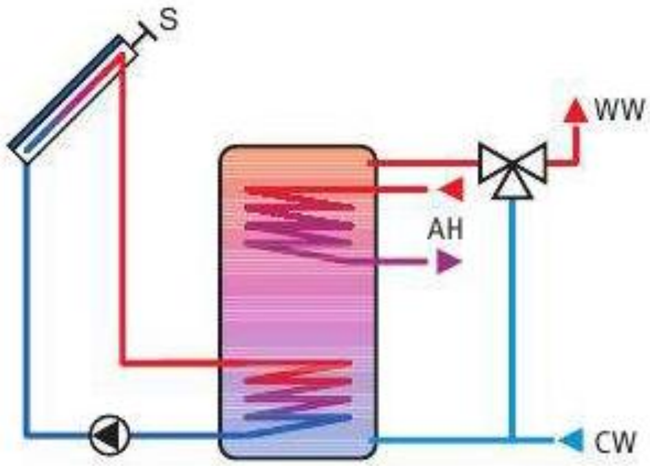
From Table 3.1, the pipe diameters for the solar circuit can be established depending on the collector surface area and the length of the pipes. These values are valid for pumped systems. The matching size for the circulating pump is also given. For thermosyphon systems, larger diameters and/or shorter lengths will probably be required to ensure proper flow; for low-flow systems the diameters and pump powers can be much lower.

Collector surface area (m^2)	**Total length (m)**				
	10	**20**	**30**	**40**	**50**
Up to 5	15/I	15/I	15/I	15/I	15/I
6–12	18/I	18/I	18/I	18/I	18/I
13–16	18/I	22/I	22/I	22/I	22/I
17–20	22/I	22/I	22/I	22/I	22/I
21–25	22/I	22/II	22/II	22/II	22/III
26–30	22/II	22/II	22/III	22/III	22/III

The Roman characters identify the respective circulation pumps. I = 30–60 W power consumption. II, III = 45–90 W.

3.3 Systems for heating domestic water

3.3.1 Standard system



The standard system has been widely accepted for use in smaller systems, and is offered by many manufacturers. It is a twin circuit (indirect) system with an internal heat exchanger for solar heat feed and a second one for top-up heating by a heating boiler. In the store there is domestic water, which can be limited to a set maximum draw-off temperature by means of thermostatic three-way blending valve. The circuitry is comparatively easy to implement, as well-tried control principles are used. The solar circuit pump is switched on as soon as the temperature in the collector is 5–8 K higher than the lower store area. When the temperature on the boiler controller for the standby volume falls below a set temperature (for example 45°C; 113°F), the boiler provides the necessary top-up heating. During this time, the space heating circuit pump (if connected) is normally switched off (domestic hot water priority switching).

3.3.2 Water heating using the flow-through principle

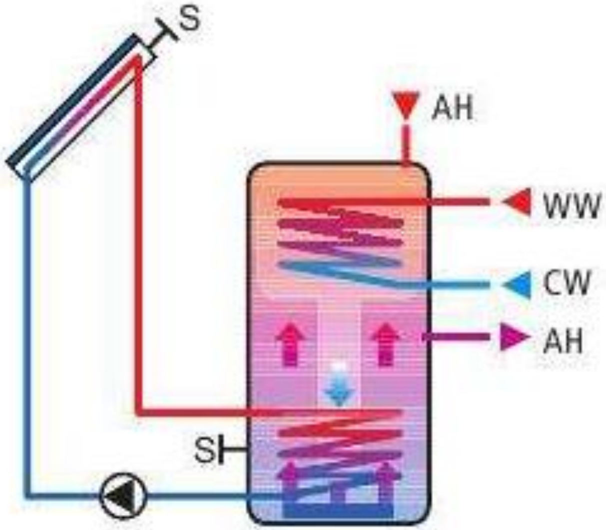
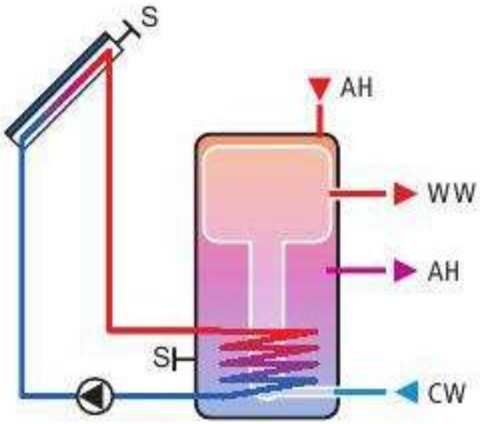


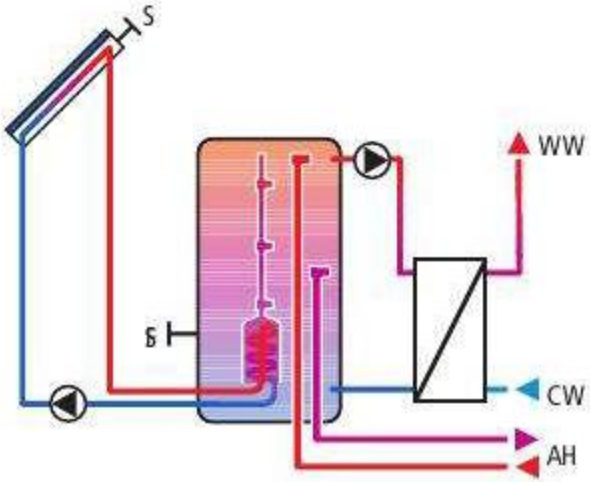
Figure 3.6 indicates a buffer store with internal charge and output heat exchanger including internal downpipe and direct auxiliary heating through the boiler (for hygienic reasons, here used exclusively for water heating).

3.3.3 Water heating by means of tank-in-tank store

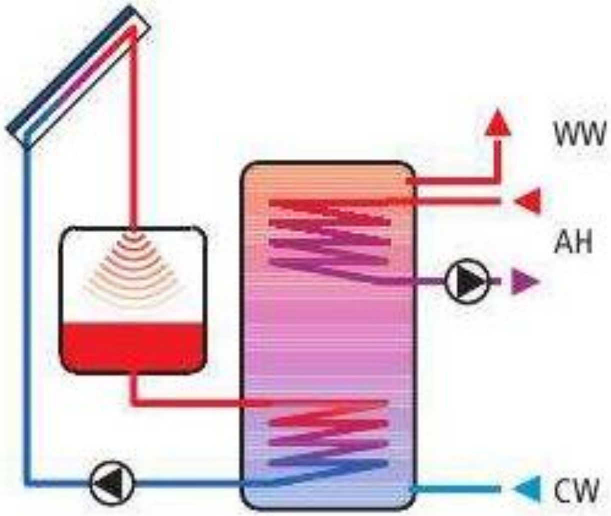


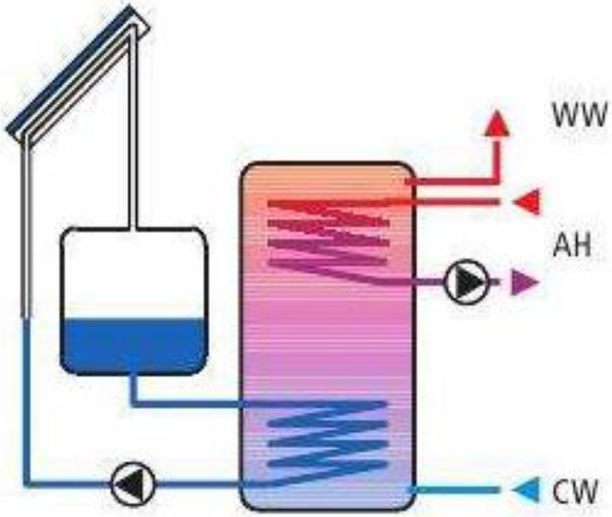
In a tank-in-tank storage system the store contains a smaller domestic water volume compared to a standard system – this results in a shorter retention time of water in the store. The surrounding buffer water is used as storage buffer for the heat.

3.3.4 Water heating over external heat exchanger



3.3.5 Drain back system





3.4 Systems for heating domestic water and space he

If a solar energy system is considered in the planning stage of the whole heati
system, and the house has a central space heating installation, it is possible to
heating to augment the space heating (combination systems). The reduced he
requirements of low-energy houses and the higher performance of modern so
energy systems encourage the trend to install solar systems with space heatin
support.

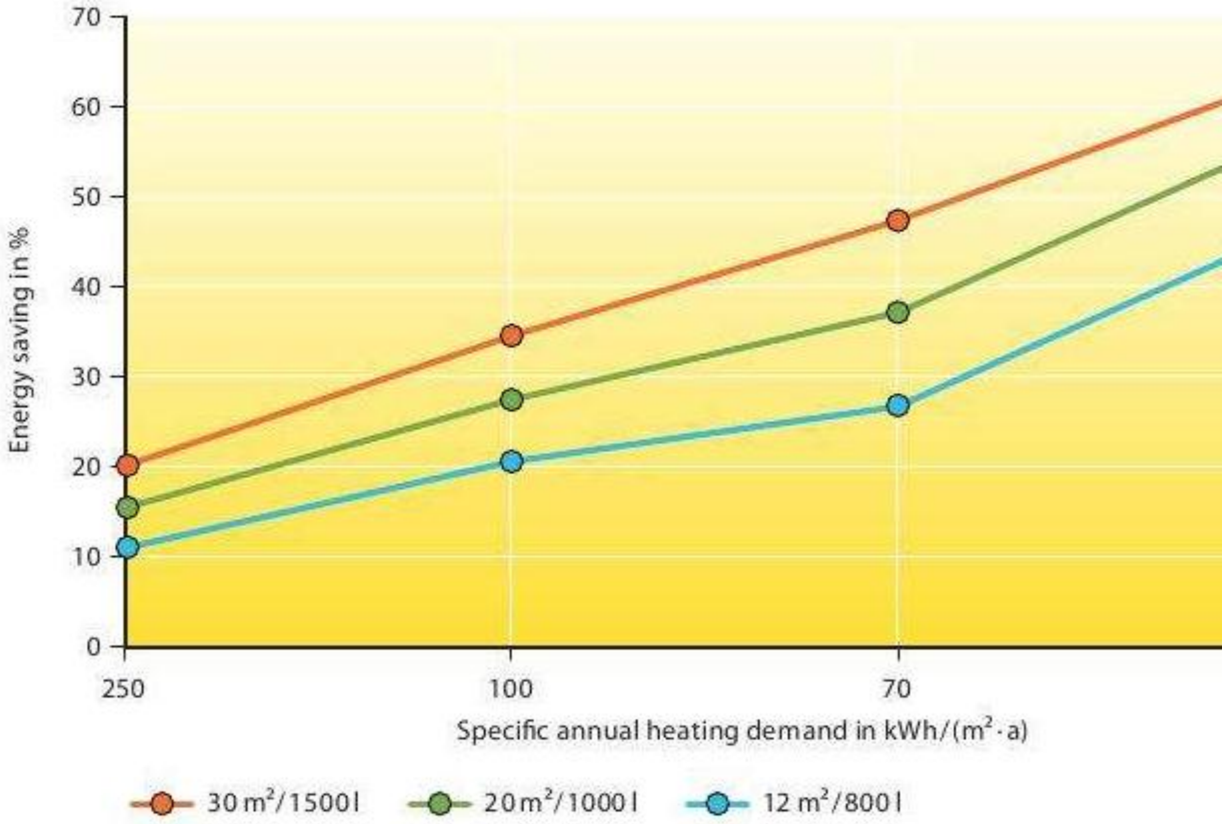


Figure 3.10.
Energy saving dependent on the system size and insulation standard (Location Hamburg)

3.5.2.3 SYSTEM EFFICIENCY

The system efficiency gives the ratio of solar heat yield to the global solar irradiance on the absorber surface with respect to a given period of time, for example one year:

$$\mathrm{SE} = \frac{\dot{Q}_\mathrm{S}}{E_\mathrm{G} A} \times 100$$

where SE is the system efficiency (%), $\dot{Q}_\mathrm{S}$ is the solar heat yield (kWh/a), E_G is the total yearly solar irradiance (kWh/m²a), and A is the absorber surface area (m²).

If the absorber surface area and the irradiance are known, and if the solar heat yield is measured (heat meter), the system efficiency can be determined:

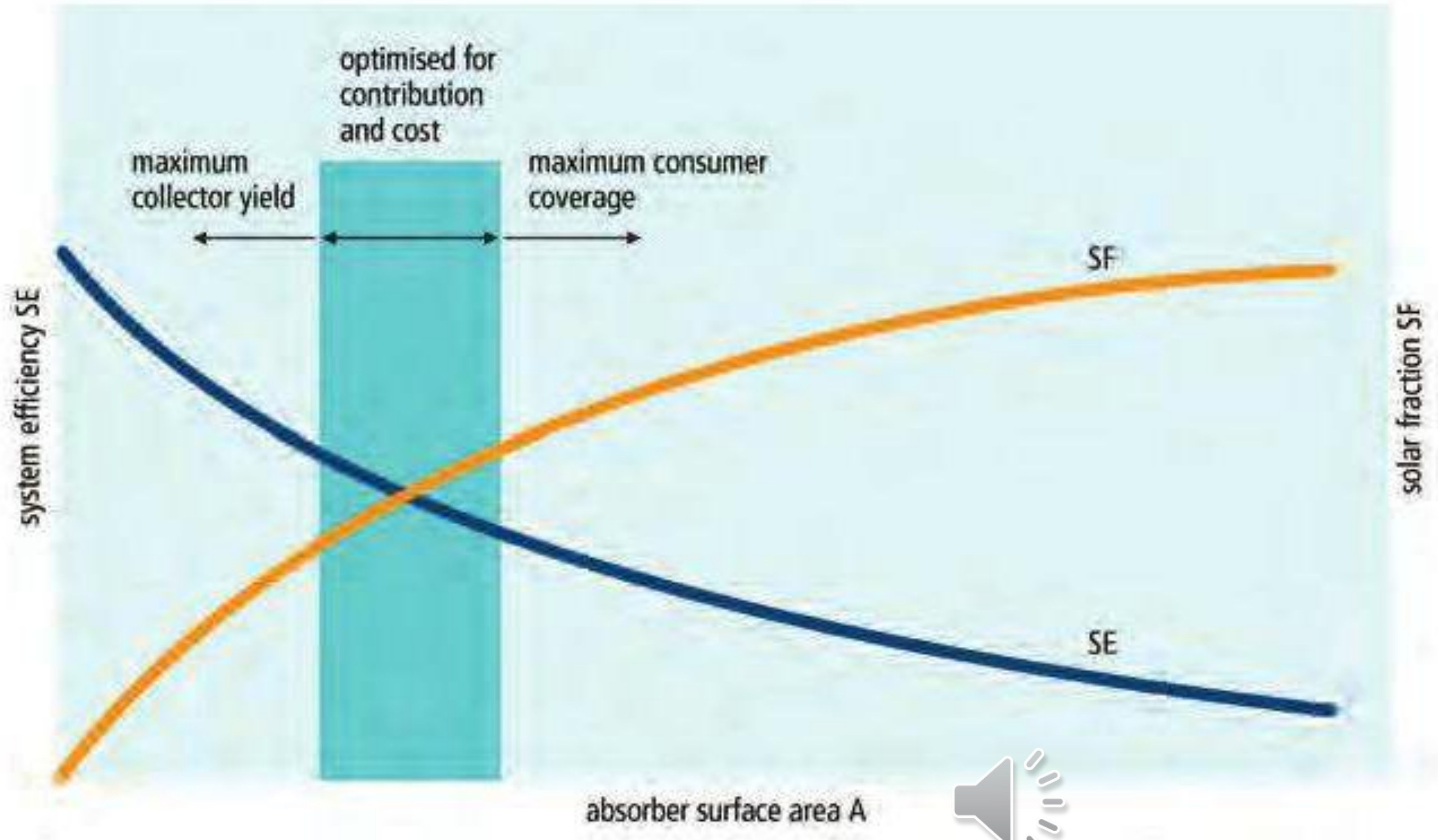
Example:

$A = 6\ \mathrm{m}^2$
$E_\mathrm{G} = 1000\ \mathrm{kWh/m^2a}$ (central Europe)
$\dot{Q}_\mathrm{s} = 2100\ \mathrm{kWh/a}$

Then the system efficiency is given by

$$\mathrm{SE} = \frac{2100\ \mathrm{kWh} \times \mathrm{m}^2 \times \mathrm{a}}{1000\ \mathrm{kWh} \times \mathrm{a} \times 6\mathrm{m}^2} \times 100 = 35\%$$

The system efficiency is strongly dependent on the solar fraction. It is higher at lower solar fractions (when the solar water heater size is small compared with the hot water demand). If the solar fraction is increased by increasing the collector area, the system efficiency is reduced, and every further kilowatt-hour that is gained becomes more expensive. This counter-effect of the two variables can be seen in Figure 3.17.



HEAT LOSSES IN PIPING AND STORES

The significance of thermal insulation is often underestimated. In the following, estimates are made of the possible thermal losses from the solar circuit, the circulation lines and the solar store.

HEAT LOSSES IN INSULATED PIPES

It is possible to make a relatively good estimate of the losses if we consider only the heat conduction through the thermal insulation.[19]

The heat losses can be formulated as follows:

$$Q_{pipe} = \frac{2\pi\lambda\Delta\theta}{\ln\,(D_{wd}/D_{pipe})} \quad \text{(W/m)}$$

where λ is the thermal conductivity of the insulating material (W/mK), D_{wd} is the outside dimension of the insulated pipe (mm), D_{pipe} is the outside diameter of the pipe (mm), ln is natural logarithm, and $\Delta\theta$ is the difference between the temperature in the pipe, θ_{pipe}, and the ambient air temperature, θ_{air} (K).

Example:

λ = 0.04 W/mK (mineral wool)
D_{wd} = 54 mm
D_{pipe} = 18 mm
$\Delta\theta$ = 30 K
In this way Q_{pipe} is calculated as

$$Q_{pipe} = \frac{2\pi \times 0.04 \text{ W} \times 30 \text{ K}}{\ln (54 \text{ mm}/18\text{mm})\text{mK}} = 6.9 \text{ W/m}$$

With a total solar circuit length of 20 m and approximately 2000 operating hours per annum, heat losses of $\dot{Q}_{pipe}$ = 6.9 W/m × 20 m × 2000 h/a = 276 kWh/a. This corresponds to an approximate annual yield for a solar energy plant with 5 m^2 of glazed flat-plate collectors of 15% ($\dot{Q}_S$ = 5 m^2 × 1000 kWh/m^2a × 0.35 = 1750 kWh/a).

If a circulation pipe is installed in the building, additional heat losses or an increased heat requirement will have to be allowed for. With a circulation line of 15 m and a running time for the circulation pumps of 2 h per day the following heat losses can be calculated:

$\dot{Q}_{circ}$ = 6.9 W/m × 15 m × 2 h/day ≈ 76 kWh/a

Therefore the resulting heat losses Q_G are

$\dot{Q}_G = \dot{Q}_{pipe} + \dot{Q}_{circ}$
= 276 kWh/a + 76 kWhA
= 352 kWh/a

This corresponds to an annual heat gain for 1 m^2 of glazed flat-plate collector surface area.

HEAT LOSSES FROM NON-INSULATED PIPES

It is also possible to estimate the heat losses for non-insulated pipes. However, as very complicated relationships exist here between convection and heat radiation, a calculation is offered for simplification purposes that uses a very much simplified equation using factors.[19] This is valid only for piping diameters below 100 mm and air temperatures around the pipes of $\theta_A = 20°C$:

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The pipe diameter must be inserted here in m.

Example:

$D_{pipe} = 0.018$ m
$\theta_{pipe} = 50°C$
$\Delta\theta = 30$ K

$$\dot{Q}_R = 0.018\ \text{m}(29.85 + 0.027 \times 50°C\sqrt[3]{50°C}) \times 30\text{K} \approx 19\ \text{W/m}$$

Therefore, when the solar circuit is not thermally insulated, heat losses arise that are almost three times higher than those for insulated piping. These heat losses will be comparable to the yield of several square metres of solar collectors, and will greatly reduce the yield of the solar system.

HEAT LOSSES FROM STORES

The heat losses from a solar store increase in proportion to the area of its upper area, A, and the temperature difference between the store and the surroundings, $\Delta\theta$:

$$\dot{Q}_{St} \approx A\Delta\theta$$

With the help of the heat loss coefficient k in W/m²K, the following equation is derived:

$$\dot{Q}_{St} = kA\Delta\theta \text{ (W)}$$

For stores the kA value is normally given in W/K.

Example:

kA value = 1.6 W/K
$\Delta\theta = 30$ K

$$\dot{Q}_{St} = 1.6 \text{ W/K} \times 30 \text{ K} = 48 \text{ W}$$

Over the course of a year this store has heat losses of

$$\dot{Q}_{St} = 48 \text{ W} \times 24 \text{ h/d} \times 365 \text{ days/a} \approx 420 \text{ kWh/a}$$

In the above case the heat losses in the store thereby correspond with the solar gain of about 1.2 m^2 of collector surface.

CALCULATION OF VOLUMETRIC FLOW AND PIPE CROSS-SECTION IN A SOLAR CIRCUIT

During system operation the volumetric flow should be large enough to cool the collector sufficiently (low average absorber temperature leads to good collector efficiency). On the other hand the flow rate through the collector should not be so large that it cannot generate a usable flow temperature. For calculating the optimum volumetric flow we make the assumption that a restriction of the temperature difference between the feed and return flows to 10 K – even in the event of good insolation – is sensible for the reasons mentioned above. The volumetric flow can then be calculated with the help of the following equation:

$$\dot{m} = \frac{\dot{Q}}{c_{G/W} \Delta \theta}$$

where $\dot{Q}$ is the usable thermal output converted by the collector (W/m^2), $c_{G/W}$ is the specific heat capacity of the solar liquid = 1.03 Wh/kg K, and $\Delta\theta$ is the temperature difference between the feed and return flows (= 10 K).

Example:

Irradiance = 800 W/m^2

Collector efficiency = 50%

$$\dot{m} = \frac{400\ \text{W/m}^2}{1.03\ \text{Wh/kg K}} \times 10\ \text{K}$$

$= 39\ \text{kg/m}^2\text{h}\ (8\ \text{lb/ft}^2\text{h})$

$= 40\ \text{l/m}^2\text{h}\ (1\ \text{gallon/ft}^2\text{h})$

The solar circuit pipe diameter can be calculated from the variables, volumetric flow $\dot{m}$ and flow speed v:

$$D = \sqrt{\frac{4\,\frac{\dot{m}}{v}}{\pi}}$$

Example:

Volumetric flow, $\dot{m}$ = 240 l/h (6 m^2 × 40 l/m^2h)
Flow speed, v = 0.7 m/s

$$D = \sqrt{\frac{4\,\frac{240\,\mathrm{ls}}{0.7\,\mathrm{hm}}}{3.1416}}$$

$$= \sqrt{\frac{4\,\frac{240\,\mathrm{dm^3h}}{25{,}200\,\mathrm{hdm}}}{3.1416}}$$

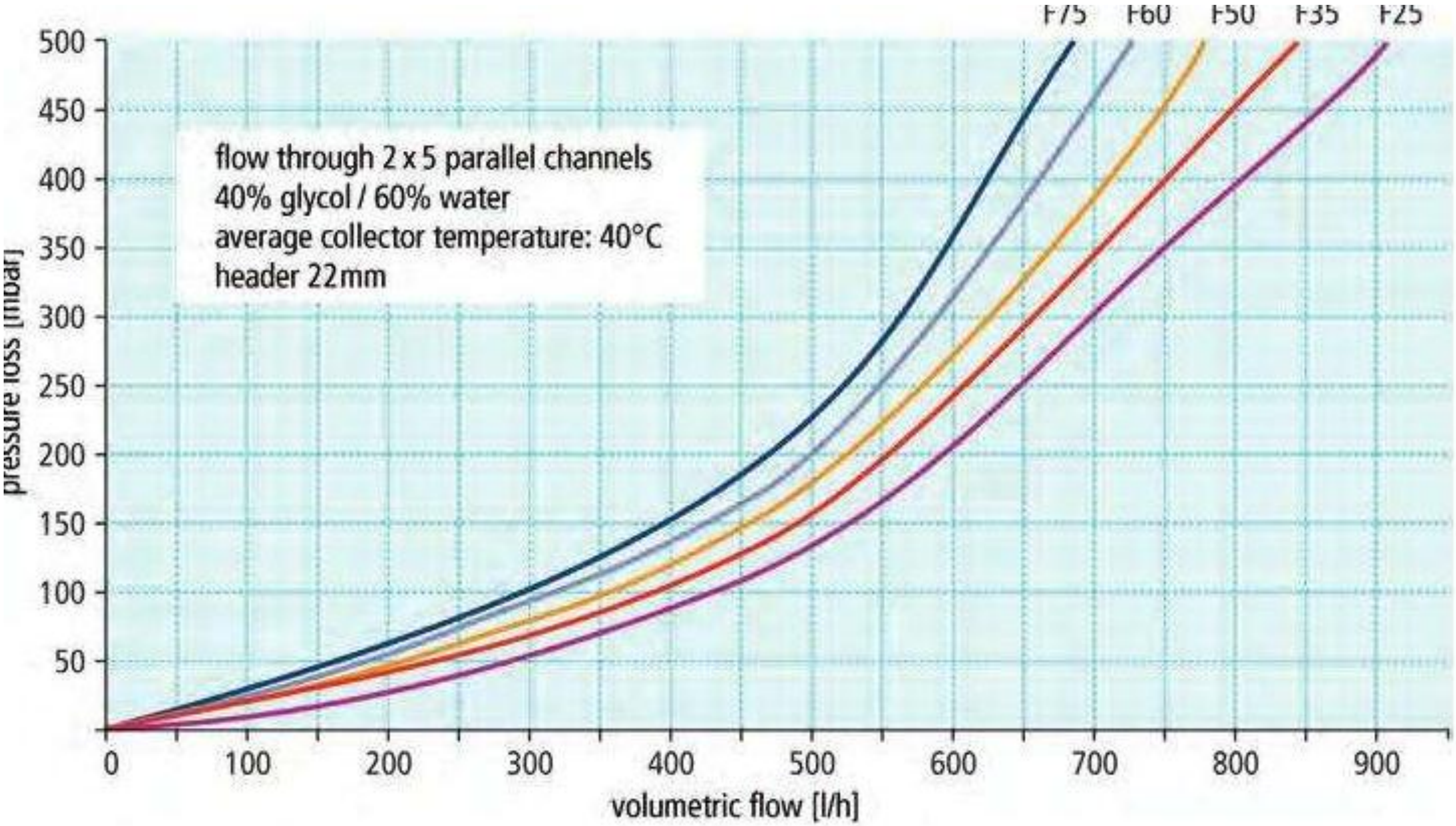
$$= \sqrt{0.0121\,\mathrm{dm}^2} = 0.1101\,\mathrm{dm} = 11.01\,\mathrm{mm}$$

The required internal diameter should therefore be at least 11 mm (o.4 inches). On the basis of Table 3.3 a copper pipe with an internal diameter of 13 mm (0.5 inches) would be selected (description Cu 15 × 1).

Pipe dimensions (outside dia. × wall thickness)	**Internal dia. (mm)**	**Contents (l/m)**
Cu 10 × 1	8	0.05
Cu 12 × 1	10	0.079
Cu 15 × 1 DN 12	13	0.133
Cu 18 × 1 DN 15	16	0.201
Cu 22 × 1 DN 20	20	0.314
Cu 28 × 1.5 DN 25	25	0.491

Note: not all diameters are on the market in all countries.

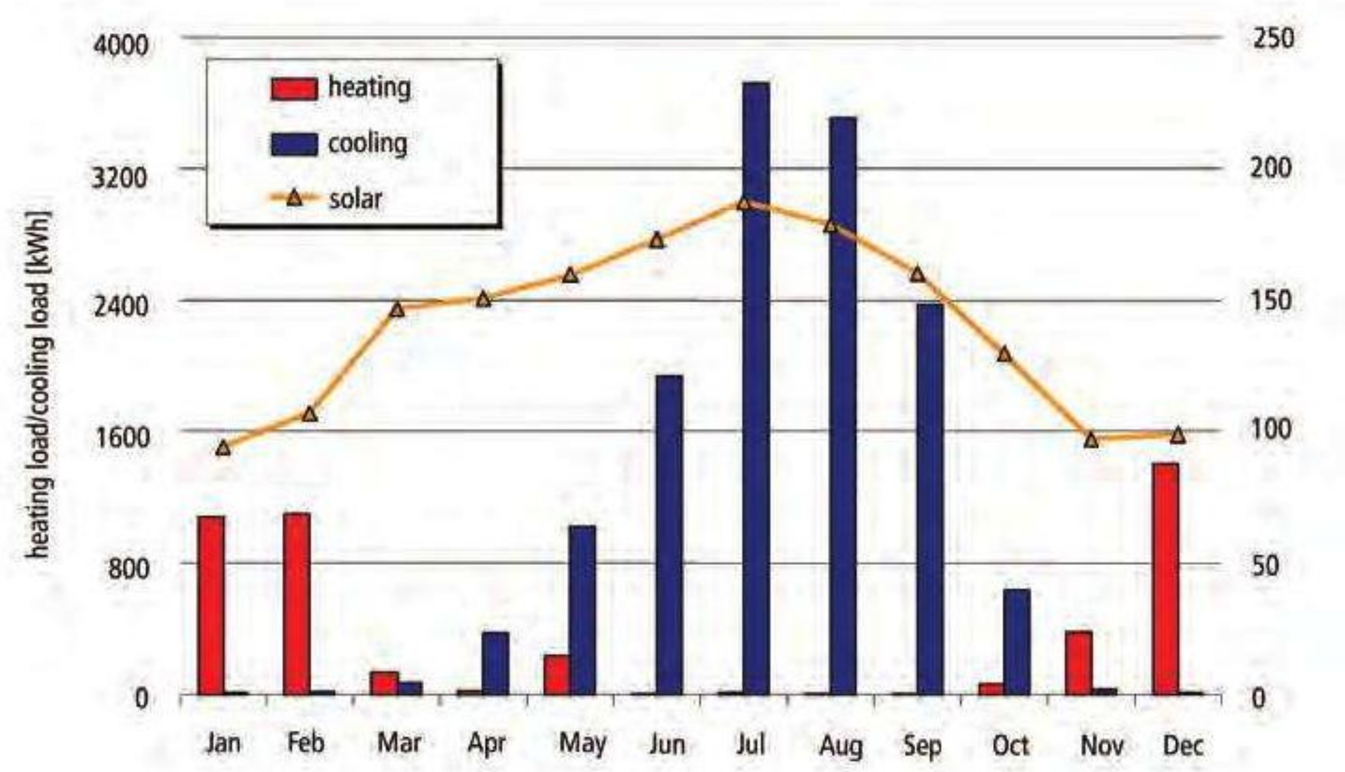
An examination of temperature-dependent length changes in pipes can be found in Chapter 4, section 4.1.7.



flow through 2 x 5 parallel channels
40% glycol / 60% water
average collector temperature: 40°C
header 22mm

mean this general category.

Another argument for solar cooling – diametrically opposed to solar space heating – is the chronological coincidence, in principle, between demand (dissipating the cooling load) and energy supply in the form of solar irradiance. Figure 9.2 illustrates this relationship for central European conditions. It shows the seasonal correspondence between irradiance and cooling load to be dissipated for a seminar room in Perpignan (southern France). It is clear that there is a very good match with cooling requirements. The result is that no large seasonal heat storage facilities are required.



9.2.1 Overview of thermally driven cooling processes

Table 9.1 shows the various thermally driven cooling processes. Among the processes available on the market, it is possible to distinguish between the closed absorption and adsorption processes and the open process of desiccant cooling.

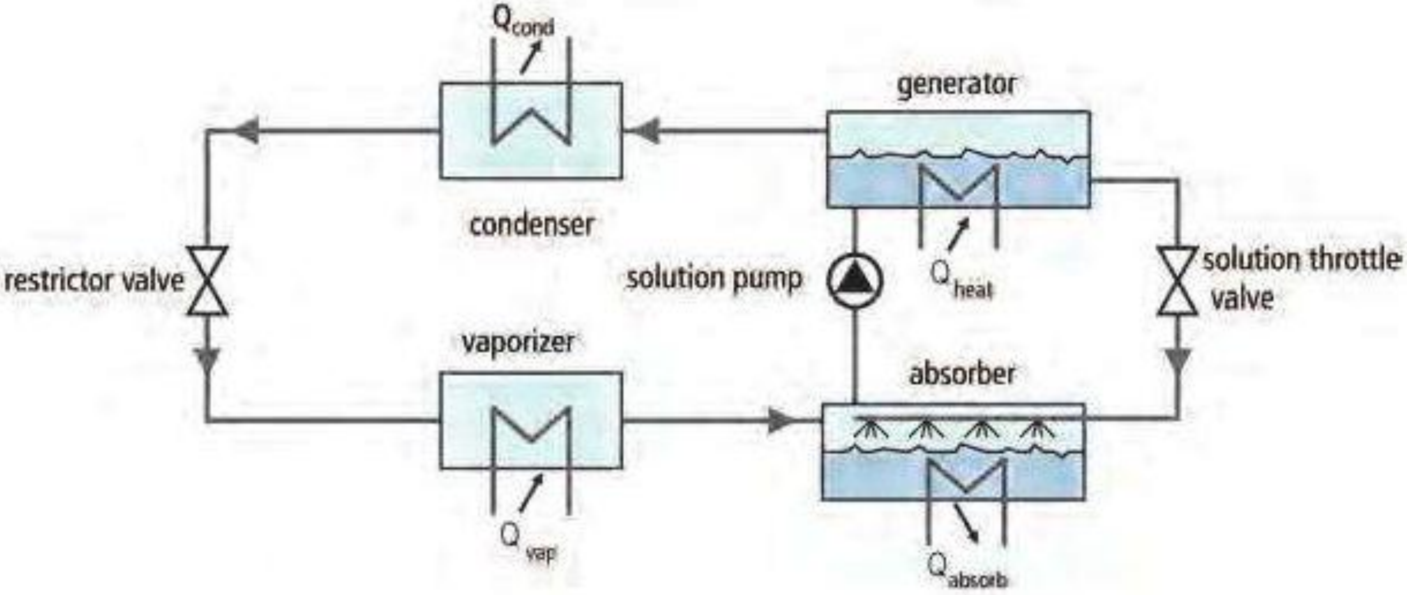
Process	Absorption	Adsorption	Desiccant cooling system
Type of air-Conditioning	Chilled water (e.g. chilled ceilings)	Chilled water (e.g. chilled ceilings)	Air-conditioning (cooling, dehumidification)

In the closed processes, the cooling medium is not in direct contact with the environment. First of all, cold water is produced. This cold water can then be used in chilled ceilings, in concrete core conditioning, or also in the classical way in the air cooler of an air-conditioning system to reduce temperature and/or humidity.

By contrast, in the open process of desiccant cooling the cooling medium (water) comes into direct contact with the air being conditioned. The cooling and dehumidification functions are directly integrated into the air-conditioning system. This is why one frequently also encounters the term *air-conditioning without refrigeration*.

9.2.2 Absorption cooling

Absorption chillers (AbCh) differ from compression chillers in that they use a thermal compressor instead of a mechanical one. Figure 9.3 shows a schematic diagram of a system of this type.



The condenser, cooling medium restrictor valve and vaporizer form the cooling part of the system, through which only the cooling medium flows. The thermal compressor comprises absorber, solution pump, generator and solution throttle valve, constituting the driving part of the system.

9.2.3 Adsorption cooling

Currently only two Japanese manufacturers of adsorption chillers (AdCh) are known on the market. Their systems are very similar in design. The physical process is identical in both chillers. The description of the function and the design is taken from the technical documentation of GBU[47]. Figure 9.4 shows the schematic structure of a low-temperature AdCh.

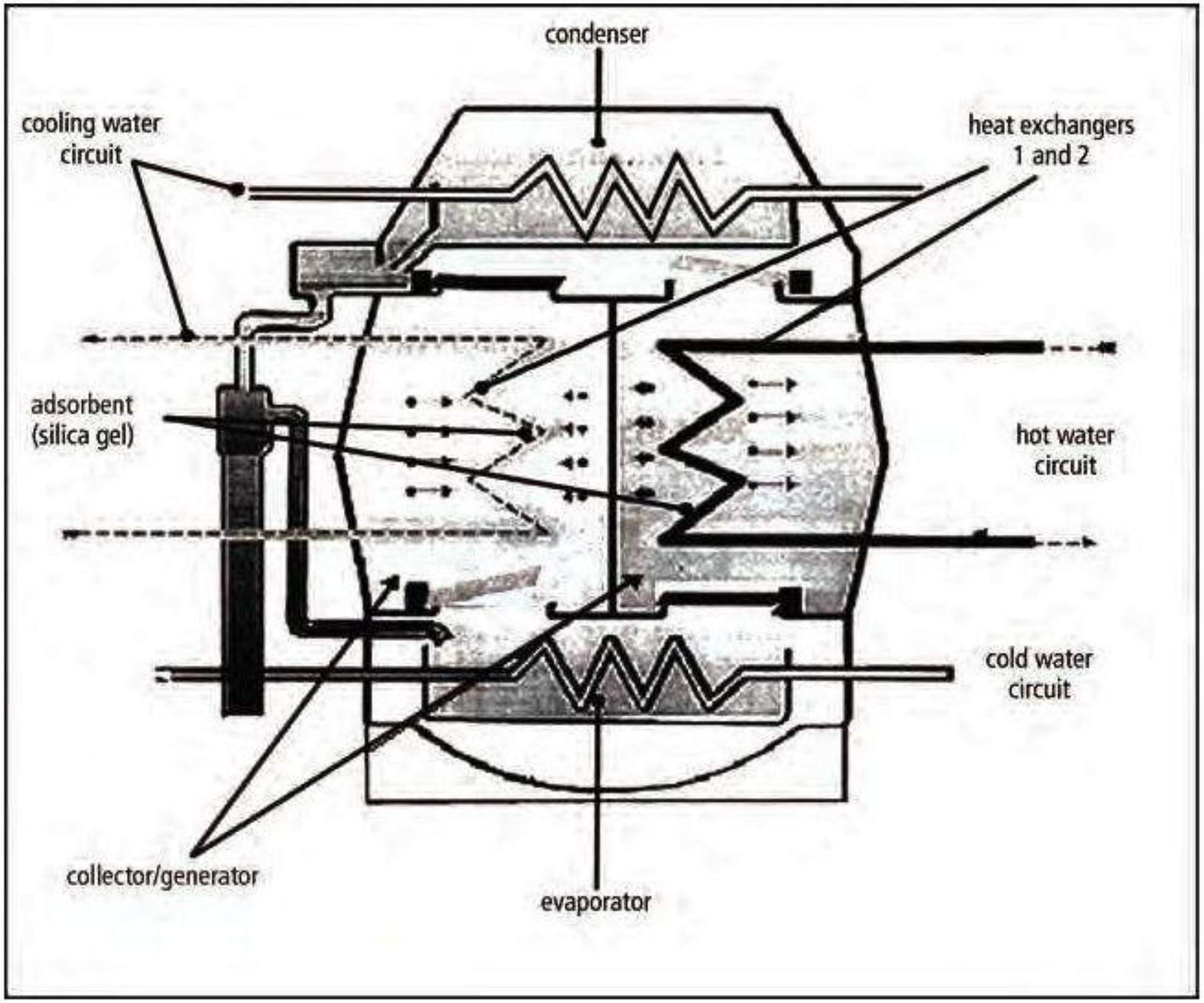
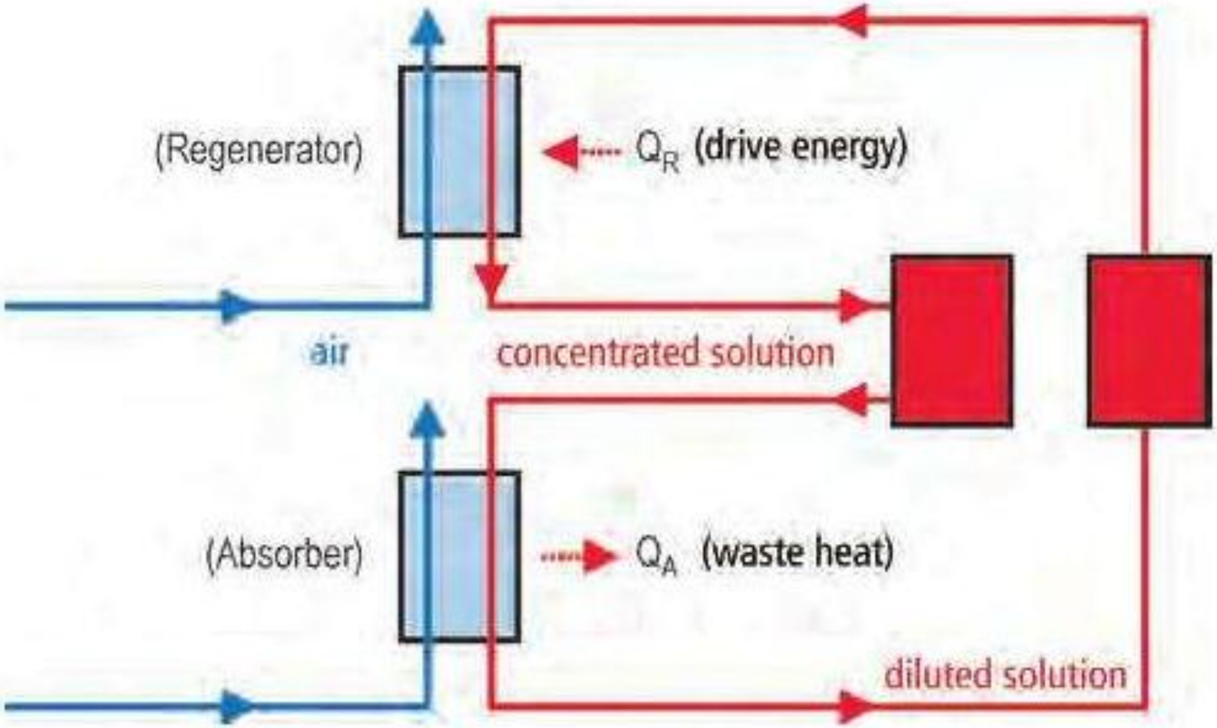


Figure 9.7 shows a highly simplified diagram of the principle of a liquid sorption system. Only the two core components – the absorber and the regenerator – are shown in the figure. Looking at the basic principle, the open process of desiccant cooling using liquid sorbents has many parallels with the closed absorption refrigeration method.



9.3 Integrated planning of solar cooling/air-conditioning systems

In contrast to solar thermal domestic hot water supply, system planning and system design for solar air-conditioning systems is significantly more complicated. Figure 9.8 shows various subsystems, which are linked to each other in a concept for a facility's solar air-conditioning system. The four subsystems are:

- building
- air-conditioning system
- heat supply
- cold supply.

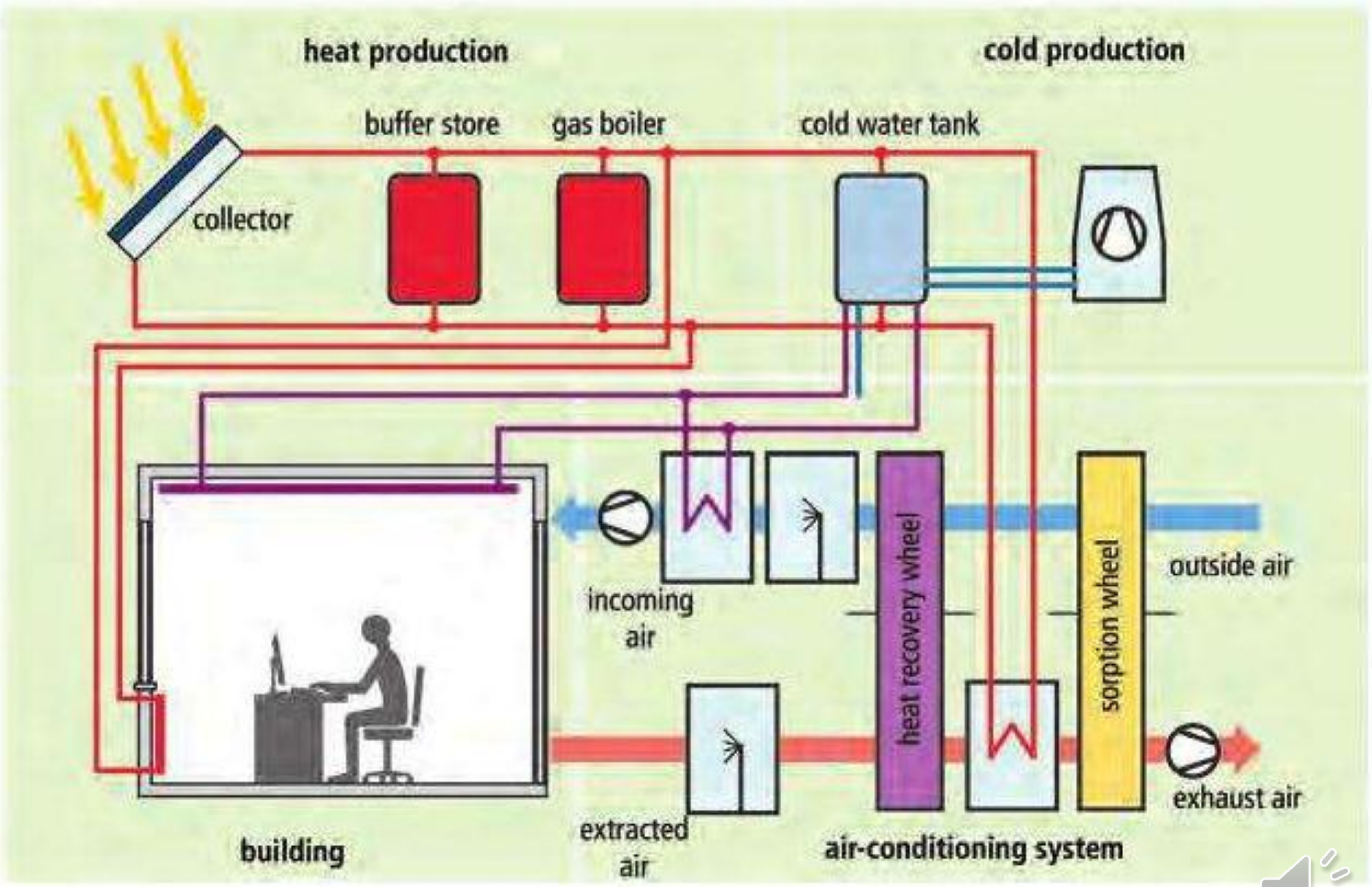
Depending on the requirements of the air-conditioning task and on the climate zone, all four subsystems or only some of them will be in use. There is a distinction to be made between full air-conditioning with all four thermodynamic conditioning functions (heating, cooling, humidification and dehumidification) and partial air-conditioning (for example only heating and cooling).

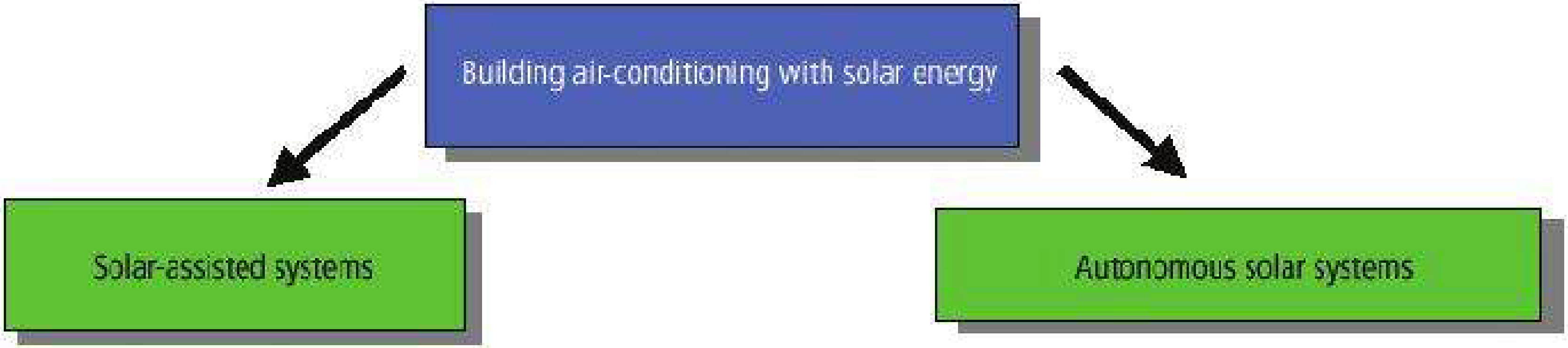
For an economically rational solution it is always important to check first whether anything can be done to the building to reduce the cooling and heating loads. The main strategies are:

- thermal insulation of the building shell
- integration of the exterior sunshade systems
- reduction of the internal loads by using energy-saving appliances.

In addition, the possibility of night ventilation should be examined early on in the planning phase, as should the possibility of activating the thermal building mass (for example using concrete construction elements as active thermal components).

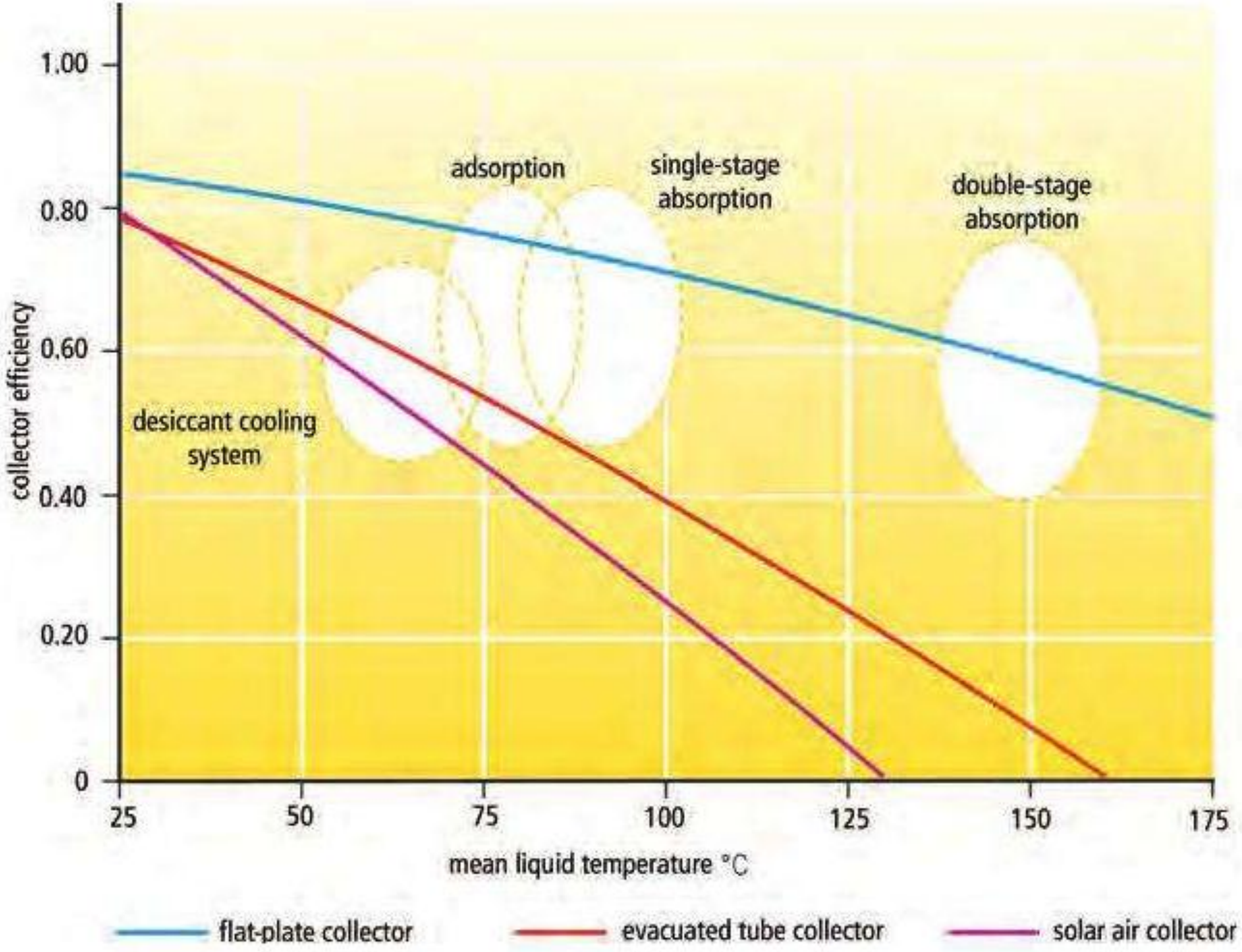
The most important steps in a good integrated planning concept are set out below. As planning should always be based around an actual project, we do not claim that this list is complete, nor that the order must necessarily be followed. This recommended method is merely intended as an aid for future planning.


heat production
cold production
buffer store
gas boiler
cold water tank
collector
heat recovery wheel
sorption wheel
outside air
incoming air
extracted air
exhaust air
building
air-conditioning system



Building air-conditioning with solar energy

Solar-assisted systems	Autonomous solar systems
Strict adherence to standards for indoor temperature and humidity requirements is possible	Slightly exceeds standard limits for indoor space requirements (limited by available irradiance and possibilities for storage)
Solar system covers a fraction of the driving heat	Solar system completely covers driving heat in summer
Solar system design: solar fraction	Solar system design: frequency distribution of indoor air temperature (and humidity)



collector efficiency
1.00
0.80
0.60
0.40
0.20
0
25
50
75
100
125
150
175
mean liquid temperature °C
adsorption
single-stage absorption
double-stage absorption
desiccant cooling system
flat-plate collector
evacuated tube collector
solar air collector

In general we can differentiate between the following systems:

- systems with solar liquid collectors
- systems with solar air collectors
- systems with solar heat input only via the heat storage tank
- systems with direct input of the solar heat into the air-conditioning technology
- systems with auxiliary heating in the heat storage tank
- systems without auxiliary heating in the heat storage tank (only with solar heat storage tanks).

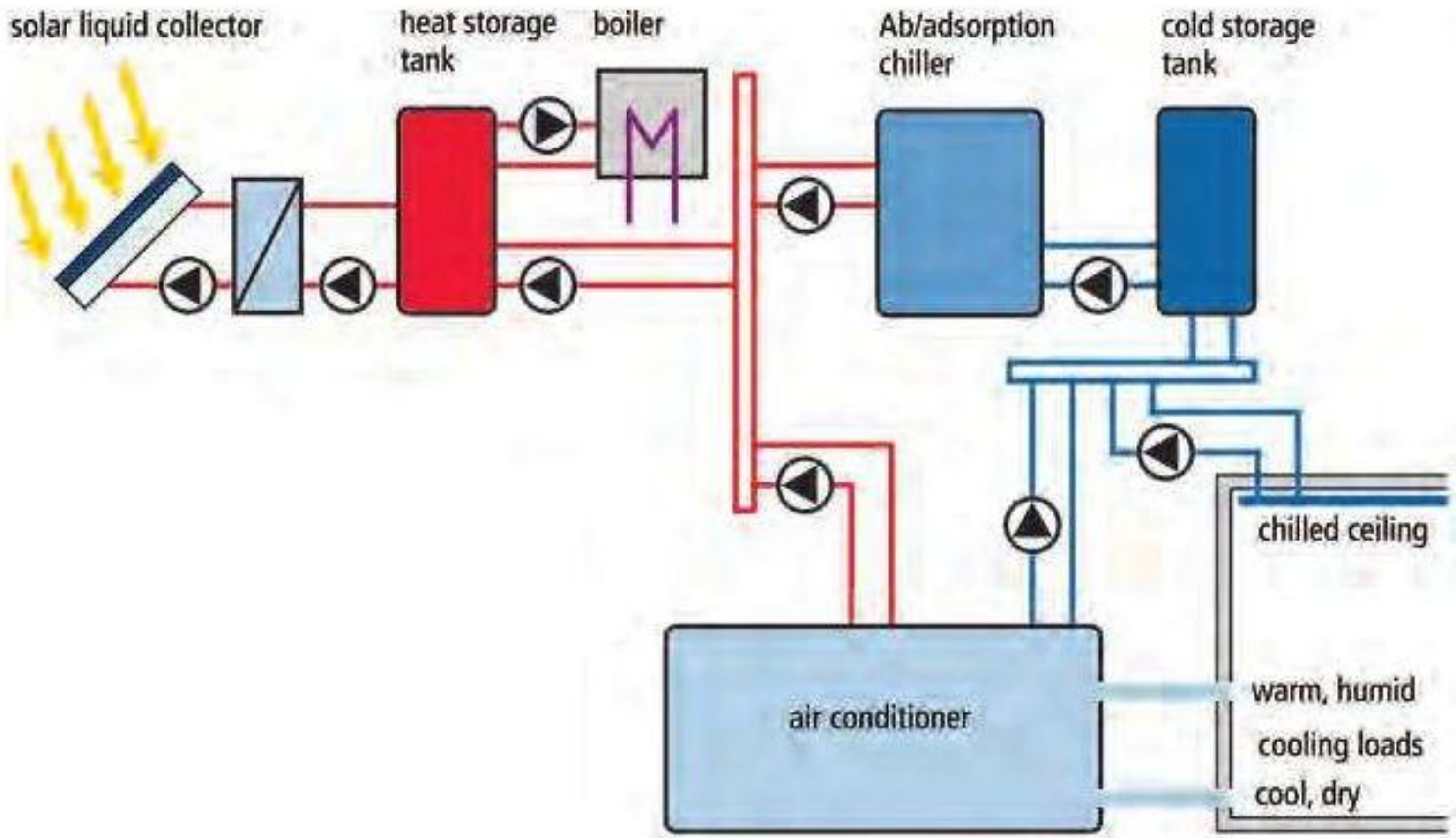


Figure 9.12 shows a solar cooling system with solar liquid collectors whereby the solar heat input is only via the heat storage tank but with no auxiliary heating in the heat storage tank. The system has the following features:

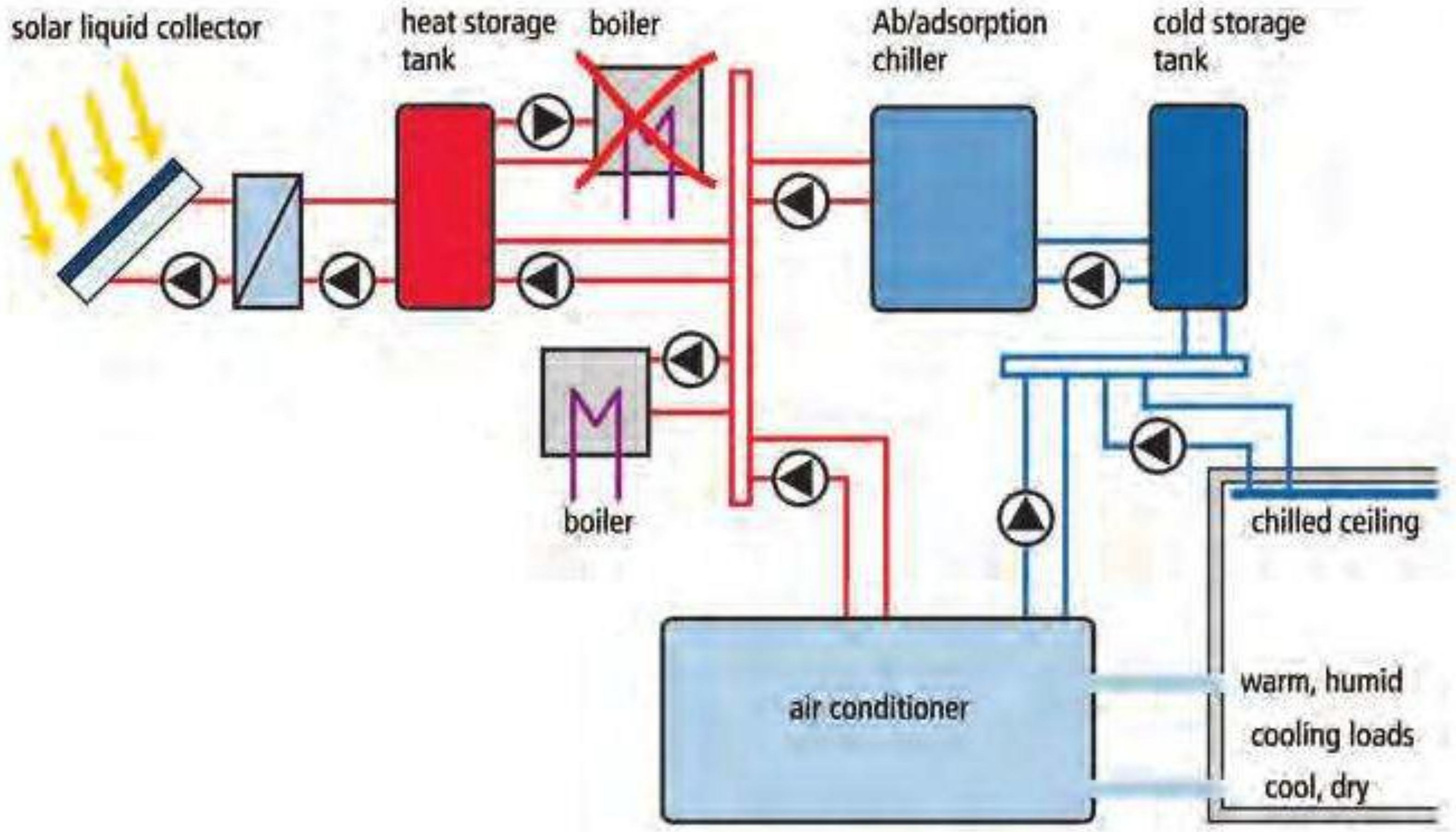
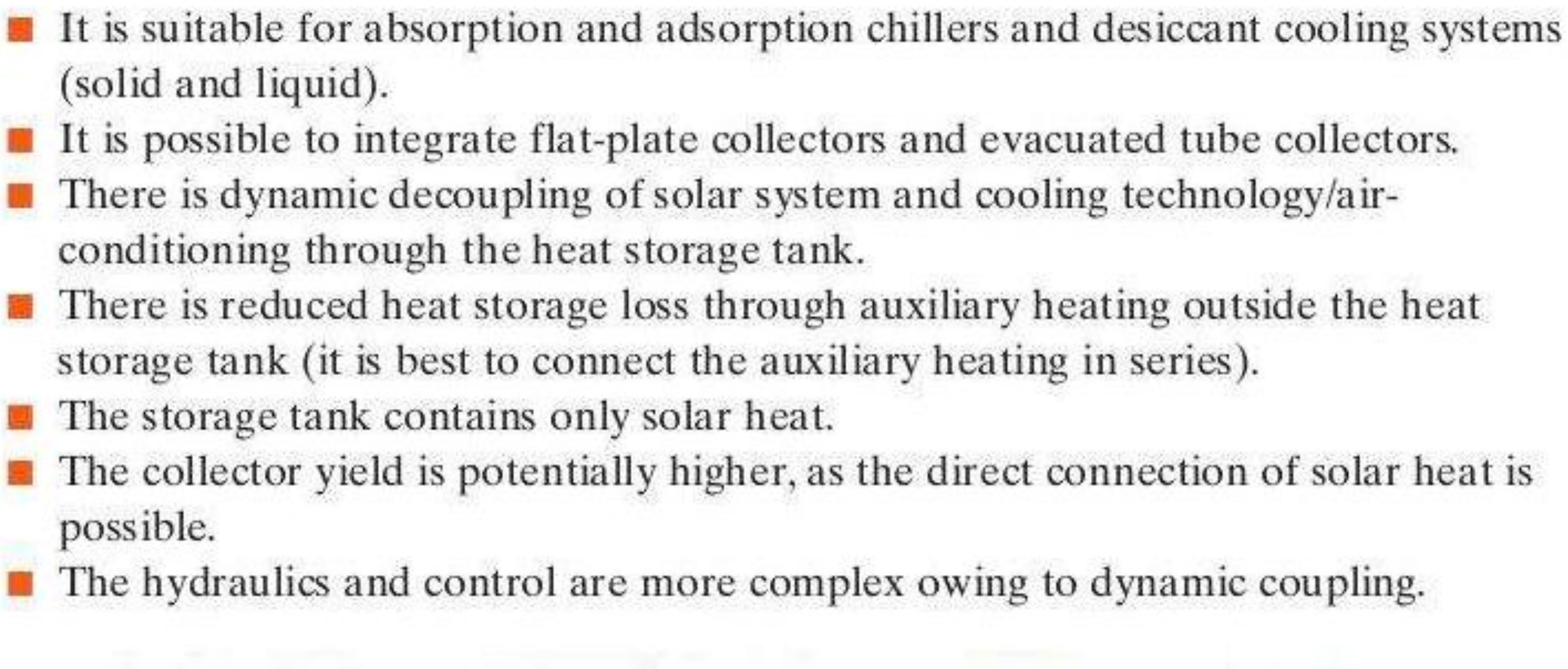


Figure 9.13 shows a solar cooling system with solar liquid collectors whereby there is direct solar heat input and solar heat input via the heat storage tank, but without auxiliary heating in the heat storage tank. The system has the following features:



- It is suitable for absorption and adsorption chillers and desiccant cooling systems (solid and liquid).
- It is possible to integrate flat-plate collectors and evacuated tube collectors.
- There is dynamic decoupling of solar system and cooling technology/air-conditioning through the heat storage tank.
- There is reduced heat storage loss through auxiliary heating outside the heat storage tank (it is best to connect the auxiliary heating in series).
- The storage tank contains only solar heat.
- The collector yield is potentially higher, as the direct connection of solar heat is possible.
- The hydraulics and control are more complex owing to dynamic coupling.

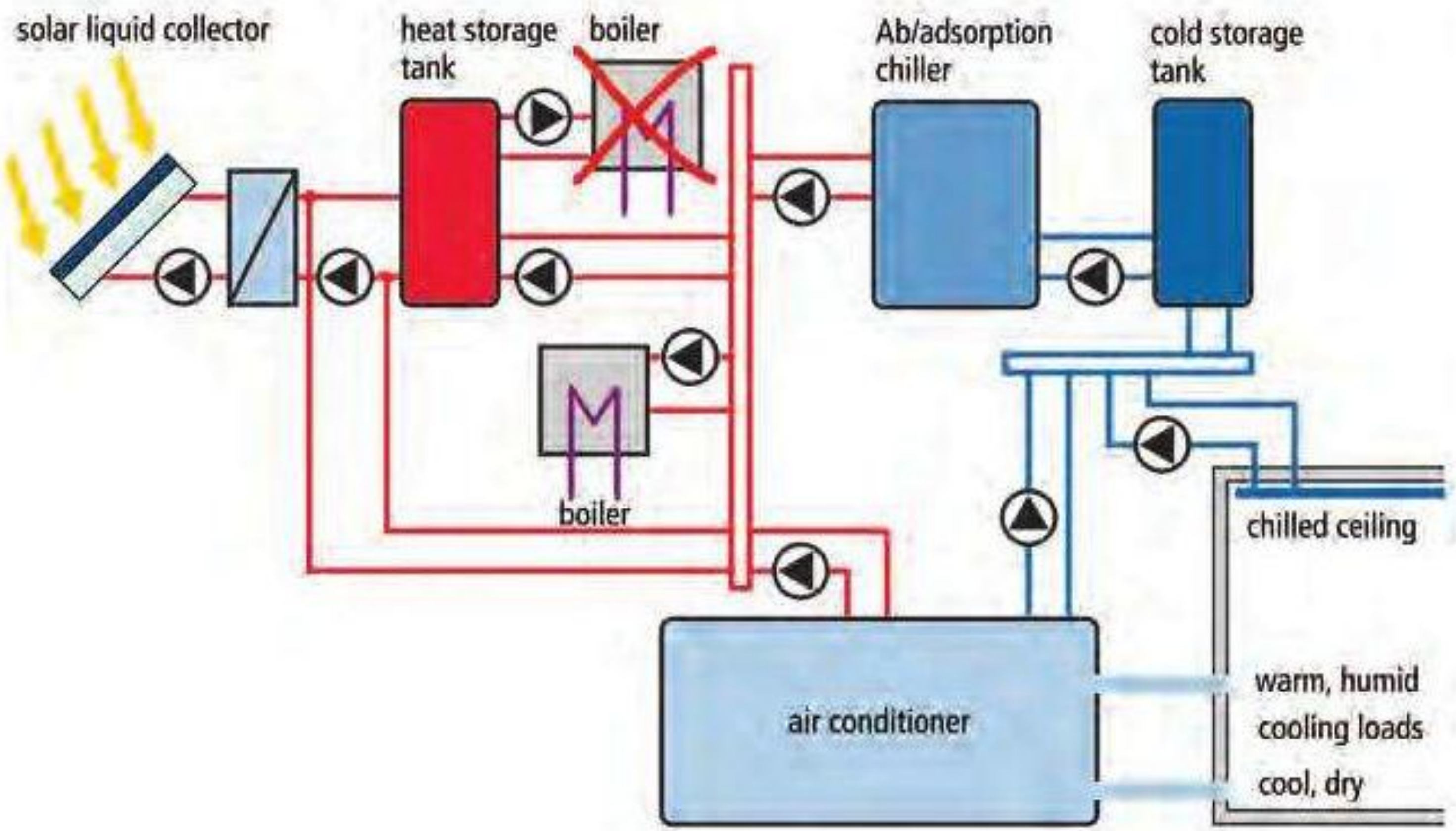


Figure 9. 14 shows a solar cooling system with solar air collectors equipped with an ambient air intake. It has direct solar heat input but no heat storage tank. The system has the following features:

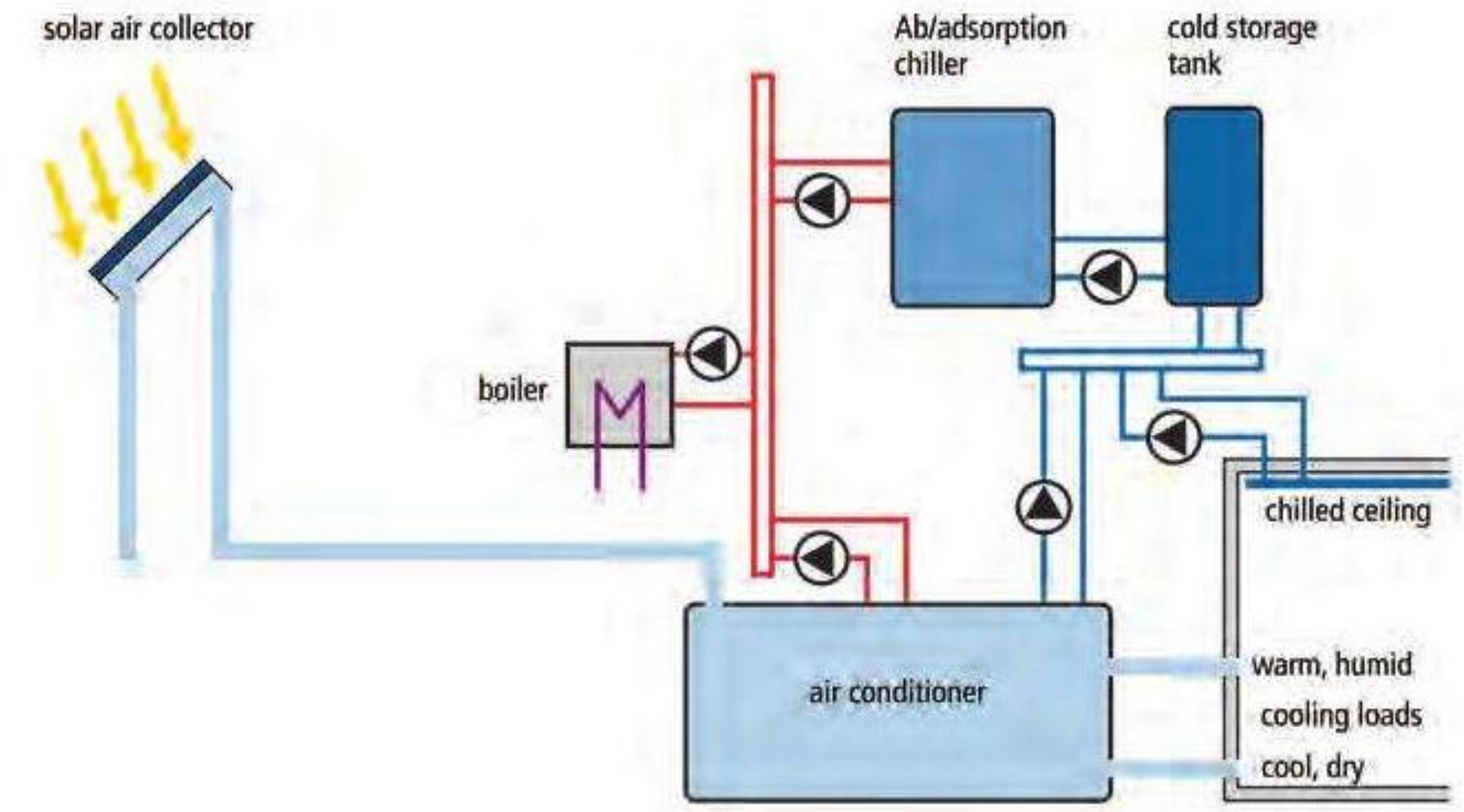


Figure 9.15 shows a solar cooling system with solar air collectors that have a regeneration air intake. It has direct solar heat input but no heat storage tank. The

The following steps for designing a solar cooling system should be carried out in every case:

(1) Calculate the cooling/heating load of the building.
(2) Optional: Calculate the cooling/heating load time series for every hour of the year based on a building simulation.
(3) Design the air-conditioning and/or cooling technology. At this point check which air-conditioning and/or cooling technology can be utilized or is suitable for the particular building.
(4) Optional: If step (2) has been carried out, decide whether the design of the air-conditioning and/or the cooling technology should be based on the peak load or whether a deviation during individual hours/days should be accepted. Quantify the potential effect of reducing the air-conditioning and/or cooling technology on the ventilation conditions, using a combined building and system simulation.
(5) Calculate the driving heat capacity of the thermally driven cooling technology.
(6) Optional: Calculate the driving heat time series for each hour of the year based on a system simulation.

on a system simulation.

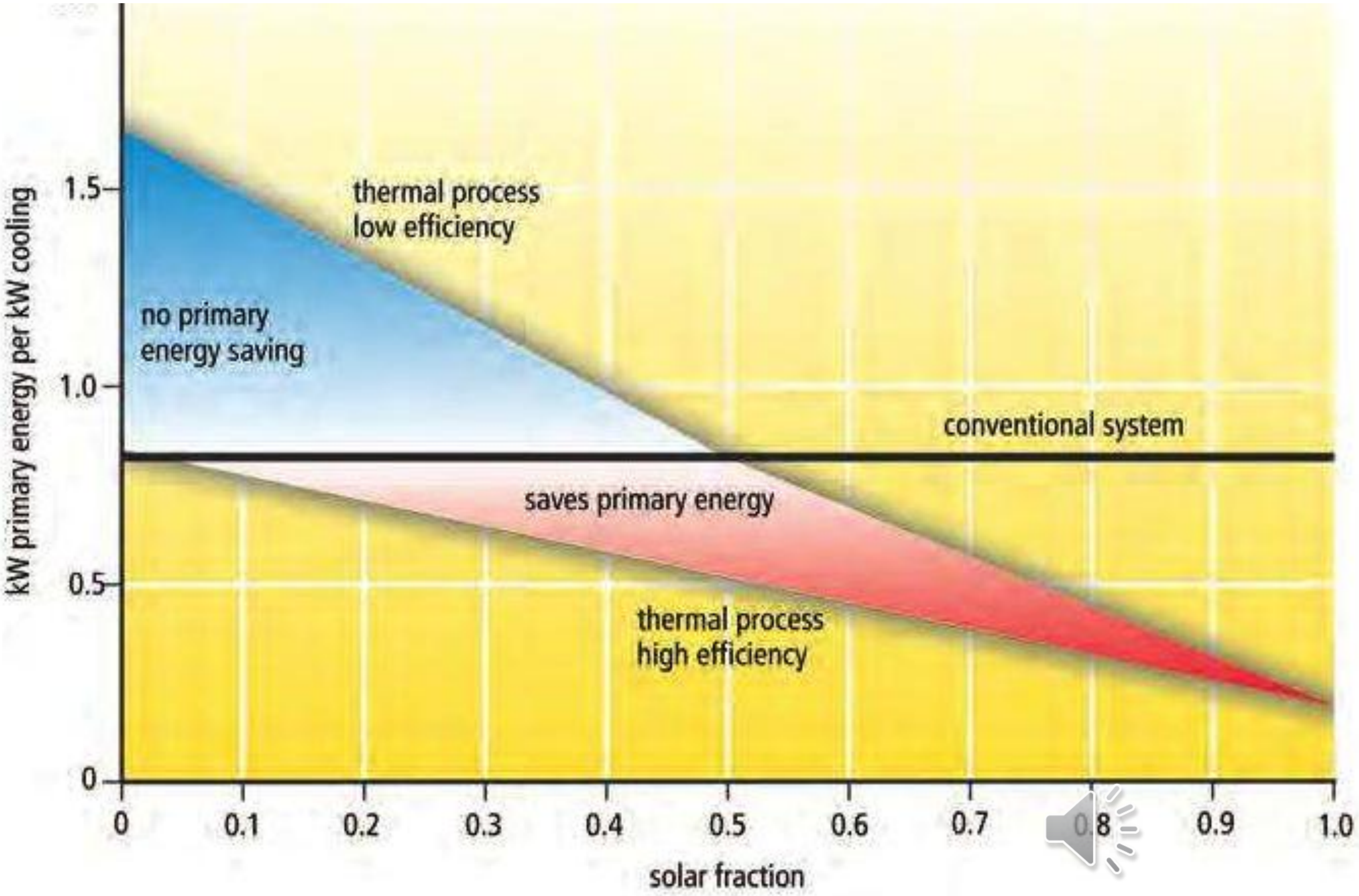
(7) Design the solar thermal system and, if intended, the heating storage tank to cover the driving heat capacity completely or partly. Design the auxiliary heating system if envisaged. In this step compare various system configurations using simulation calculations; this makes sense if (and only if) step (6) was carried out. If a façade-integrated solar system is planned or one that partly shades the façade, then at this point it can make sense to recalculate the heating/cooling load of the building according to step (1).

(8) Calculate all the energy and water consumption in the entire system.

(9) Calculate the costs of the solar system and the auxiliary heating system according to step (7). Take into consideration both the consumer price and the price per unit for the electricity and heat.

(10) Calculate the costs of the entire system.

(11) If the costs are not acceptable, iterative steps are recommended from step (3) or from step (7).


kW primary energy per kW cooling
1.5
1.0
0.5
0
thermal process
low efficiency
no primary
energy saving
conventional system
saves primary energy
thermal process
high efficiency
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
solar fraction

WATER HEATING IN SWIMMING POOLS

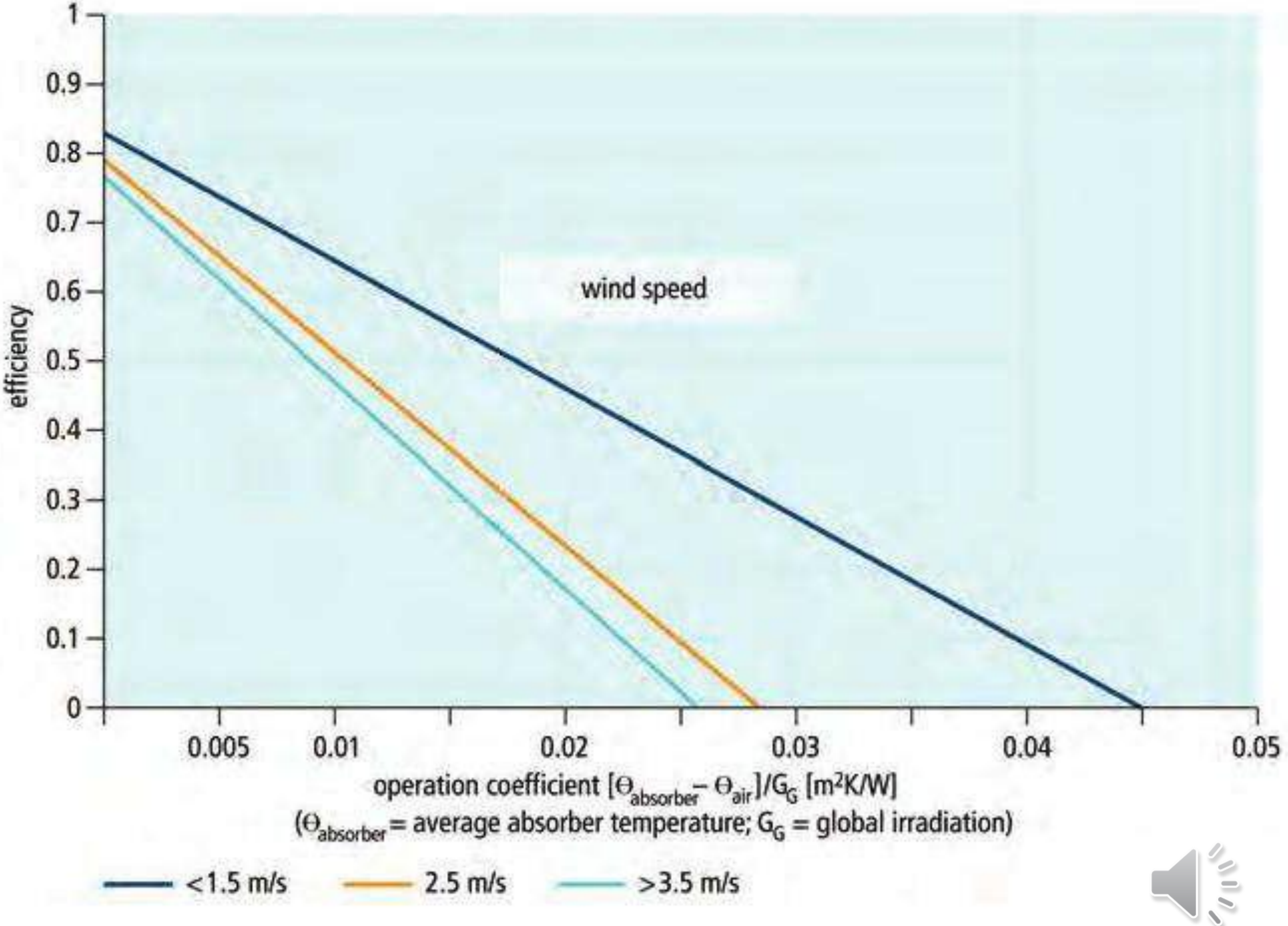
For hygienic reasons swimming pools are treated with chlorine. This results in problems with corrosion when using copper or brass. All components which come into contact with chlorine should be made of plastics, black steel or titanium.

CAPILLARY EFFECT

According to the law of communicating pipes, liquids in pipes that are connected to one another will always be at the same level, independently of the shape of the pipes. The exception to this is that, in a narrow pipe (a *capillary*), the liquid is either at a higher level (for a wetting liquid, such as soldering tin) or a lower level (for a non-wetting liquid, such as mercury).

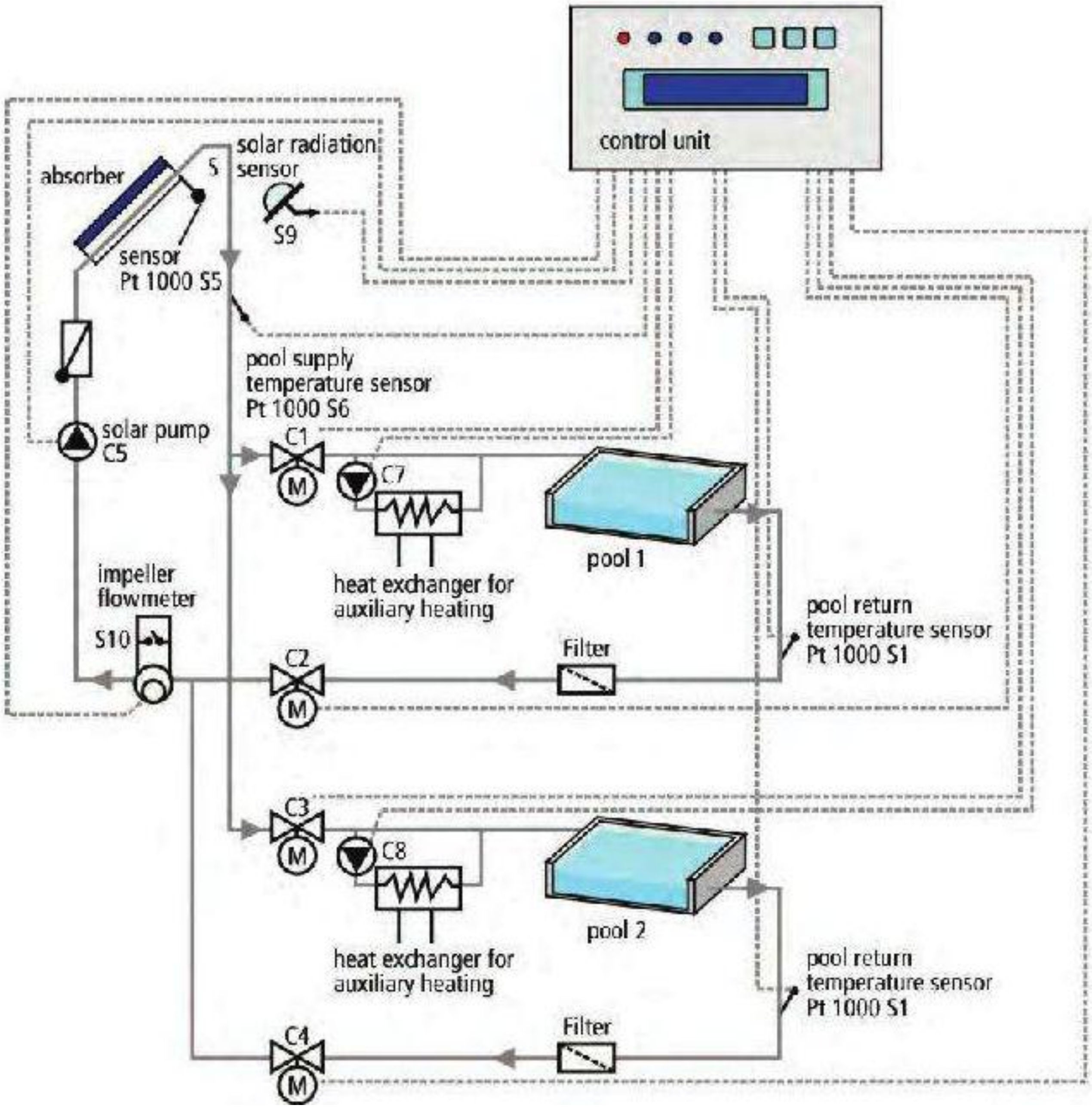
Solar heating of open-air swimming pool water has some decisive advantages over other methods of using solar energy thermally:

- *Temperature level.* The required temperature level is comparatively low, at 18–25°C (64.4–77°F). This permits the use of less expensive polypropylene absorbers.
- *Solar radiation and time of use.* The swimming season coincides with the time of the highest solar radiation. Commonly at latitudes in central Europe open-air pools are operated from the beginning or middle of May until the middle of September. During this period approximately 65–75% of the annual solar radiation occurs. At lower latitudes, the swimming season can be longer. Because of higher air temperatures the need for swimming pool heating may decrease, but with a smaller collector high efficiencies can be reached.
- *Simple system design.* The pool water flows directly through the absorber, powered by the filter pump. The storage tanks normally required for solar energy systems are not required, as the pool itself takes over this function.


1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
efficiency
wind speed
0.005
0.01
0.02
0.03
0.04
0.05
operation coefficient [$\Theta_{absorber} - \Theta_{air}$]/$G_G$ [m^2K/W]
($\Theta_{absorber}$ = average absorber temperature; G_G = global irradiation)
<1.5 m/s
2.5 m/s
>3.5 m/s

7.2.4.2 HEAT EXCHANGERS

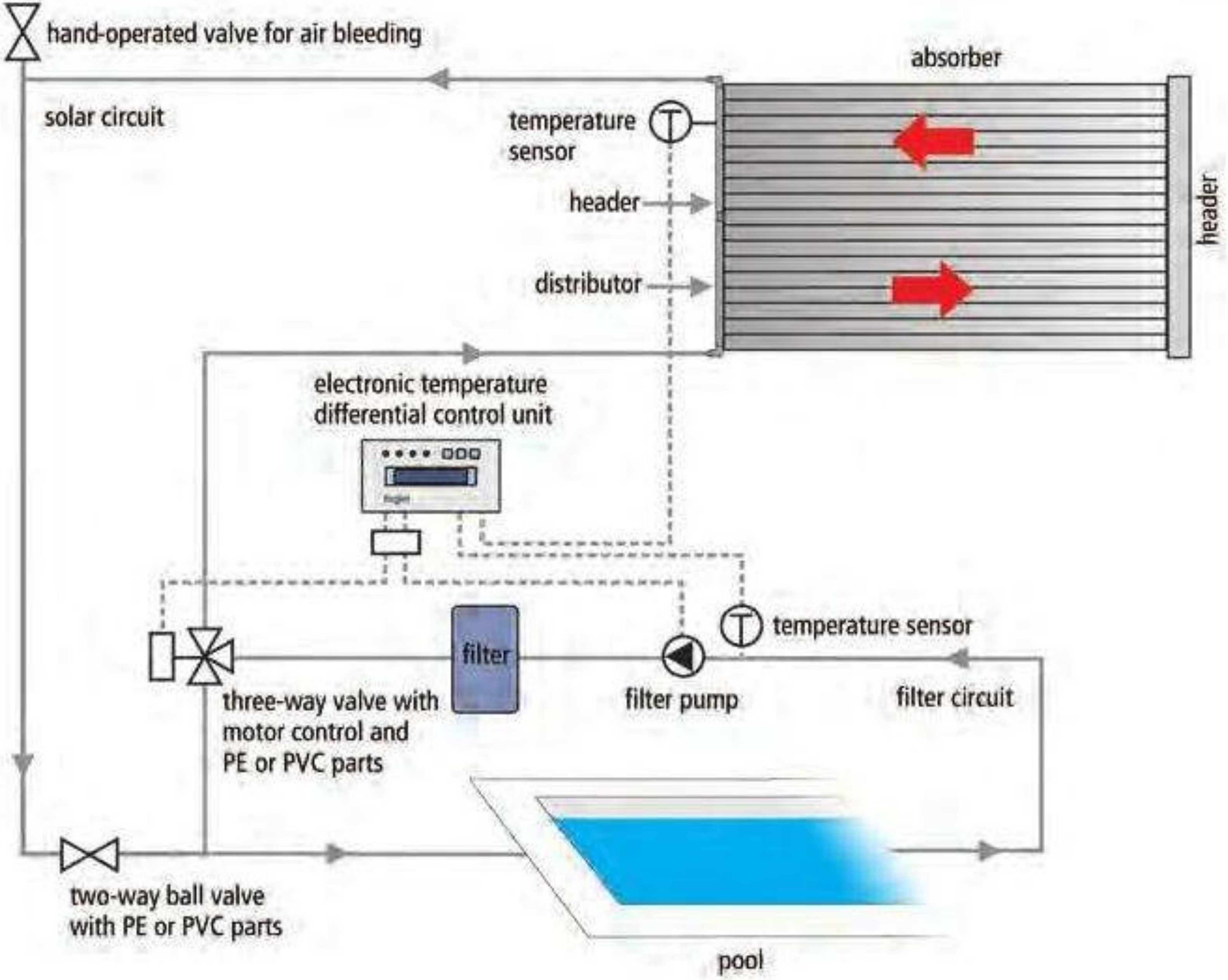
Standard solar systems for open-air pool heating have a simple system construction, in which no heat exchanger is necessary. If, however, a second type of heating is required, heat exchangers are necessary. The heat exchanger must naturally meet the same material requirements as on the swimming pool water side. Stainless steel (V4A or St.1.4571) is generally used here. All sorts of heat source, such as heat pumps or gas heating boilers, can be connected and a temperature sensor positioned for control purposes. Certain system configurations (see section 7.3), however, require the use of heat exchangers, which are described in more detail in sections 2.4.4 and 5.4.


control unit
solar radiation sensor
S
absorber
S9
sensor
Pt 1000 S5
pool supply
temperature sensor
Pt 1000 S6
solar pump
C5
C1
M
C7
pool 1
heat exchanger for
auxiliary heating
impeller
flowmeter
S10
C2
M
Filter
pool return
temperature sensor
Pt 1000 S1
C3
M
C8
pool 2
heat exchanger for
auxiliary heating
pool return
temperature sensor
Pt 1000 S1
C4
M
Filter

7.3 Systems

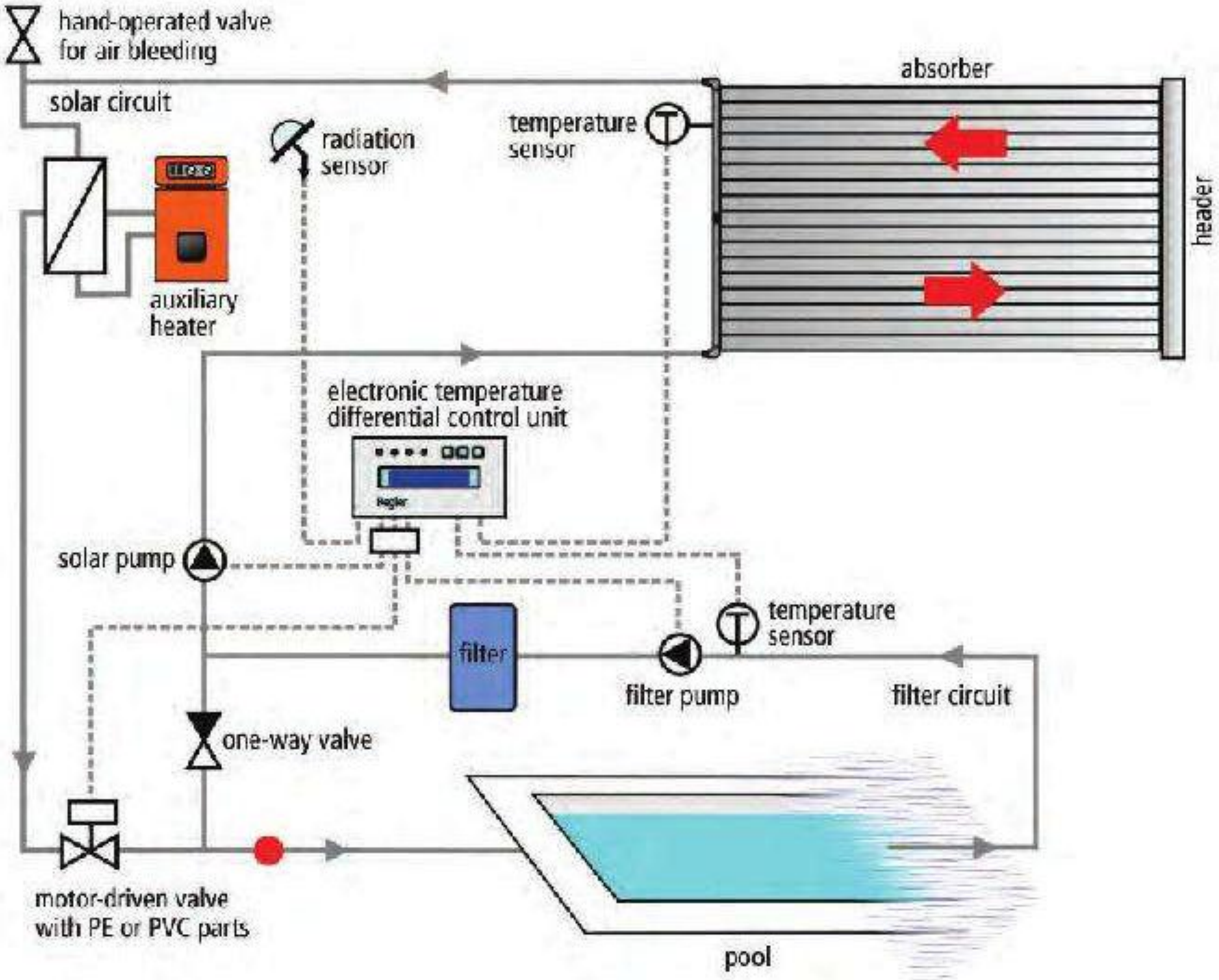
7.3.1 Solar private open-air pool heating

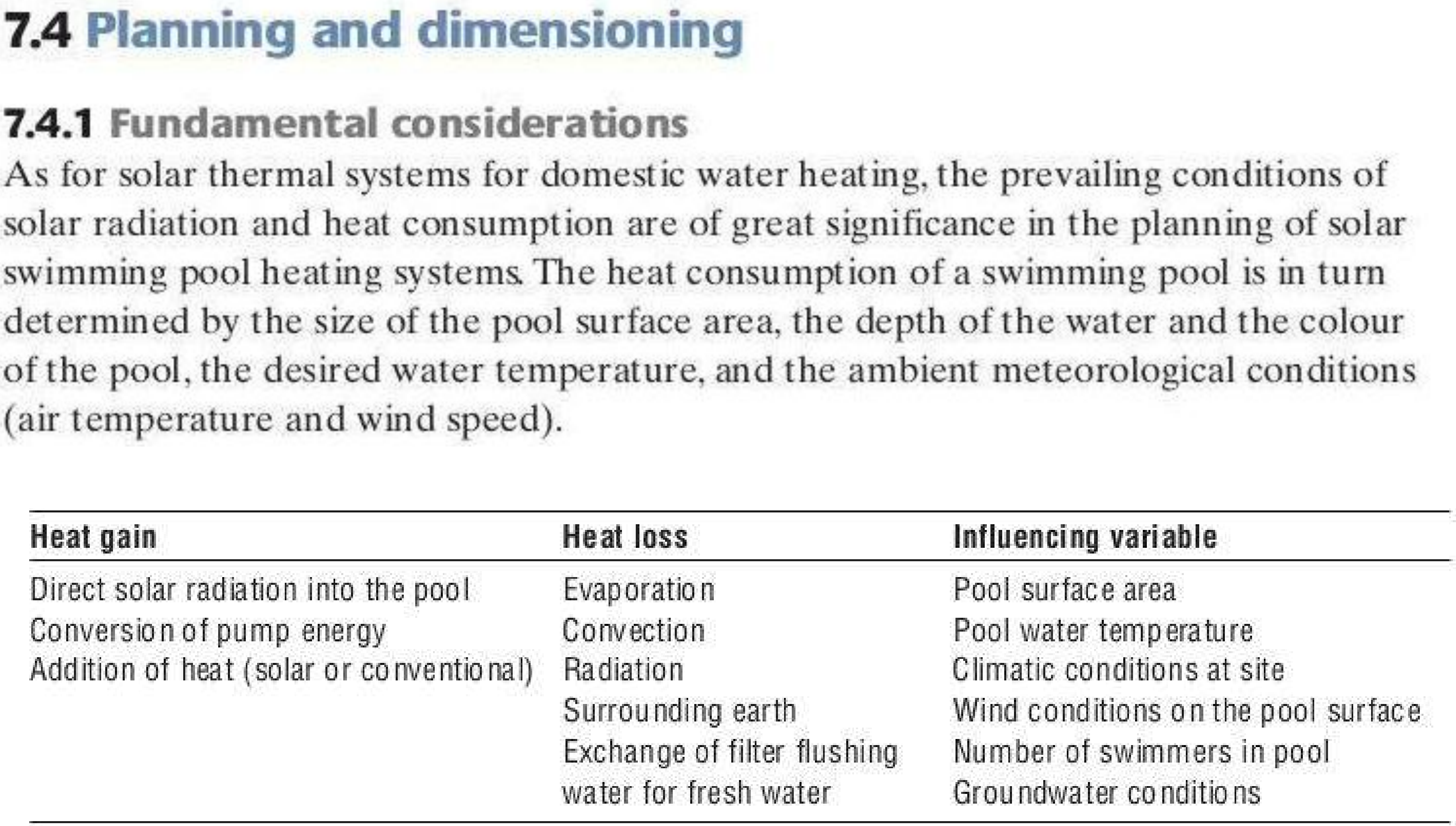
In the case of private swimming pools the pool surface is seldom larger than 100 m^2 (1076 ft^2). Commonly only simple filter circuits are installed here. Conventional auxiliary heating systems are being installed less and less. As for domestic water heating systems, solar systems are now being offered as complete packages with all necessary components. The absorber surface area is dimensioned according to the size of the pool (see planning section) and is thereby offered in different sizes. There are several methods of implementing the hydraulic circuit and the operation of the absorber circuit. The two most sensible and most frequently used systems are described in detail in the following sections.


hand-operated valve for air bleeding
absorber
solar circuit
temperature sensor
header
distributor
header
electronic temperature differential control unit
temperature sensor
filter
filter pump
filter circuit
three-way valve with motor control and PE or PVC parts
two-way ball valve with PE or PVC parts
pool

7.3.2.4 INTEGRATION OF AUXILIARY HEATING

Conventionally operated auxiliary heating is necessary if the pool water has to be maintained at a constant temperature. Some open-air pools like to offer their visitors warm swimming pool water independently of the sunshine, which requires auxiliary heating when the solar radiation is insufficient.





7.4 Planning and dimensioning

7.4.1 Fundamental considerations

As for solar thermal systems for domestic water heating, the prevailing conditions of solar radiation and heat consumption are of great significance in the planning of solar swimming pool heating systems. The heat consumption of a swimming pool is in turn determined by the size of the pool surface area, the depth of the water and the colour of the pool, the desired water temperature, and the ambient meteorological conditions (air temperature and wind speed).

Heat gain	Heat loss	Influencing variable
Direct solar radiation into the pool	Evaporation	Pool surface area
Conversion of pump energy	Convection	Pool water temperature
Addition of heat (solar or conventional)	Radiation	Climatic conditions at site
	Surrounding earth	Wind conditions on the pool surface
	Exchange of filter flushing water for fresh water	Number of swimmers in pool
		Groundwater conditions

1.3 Climate change and its consequences

Based on the apparent finite energy resources, the environment and the climate are being dramatically changed and damaged to an ever-greater extent by the burning of fossil fuels. The cause of this is the emission of hazardous substances such as sulphur dioxide, oxides of nitrogen and carbon dioxide connected with the incineration process.

- Sulphur dioxide and oxides of nitrogen are among those hazardous substances that play a significant part in causing acid rain.
- Carbon dioxide (CO_2) is the greenhouse gas that is mainly responsible for the heating up of the earth's atmosphere. For many thousands of years the CO_2 concentration remained nearly constant. Over the past 200 years the CO_2 concentration has increased from approximately 270 ppm*) to currently 385 ppm at an ever-increasing rate.

Other greenhouse gases we emit include:

- Methane (CH_4) from agriculture
- Nitrous oxide (N_2O).

GREENHOUSE EFFECT

The earth–atmosphere system absorbs the visible, shortwave radiation from the sun in the wavelength range of approximately 0.3–3.0 µm. The result of this is heating up of the earth's surface and the atmospheric layers. In turn, each heated body radiates according to its temperature. However, this heat emission takes place in a longer wavelength range of between 3.0 and 30 µm.

NATURAL GREENHOUSE EFFECT

CO_2 molecules can retain part of this heat energy radiated back from the earth's surface and the atmosphere. This process is called the *greenhouse effect*, as the CO_2 layer in the atmosphere can be compared with the glass planes in a greenhouse, which let the light in but keep the heat from getting out. With the natural content of CO_2 in the earth's atmosphere the temperature of the earth is currently +15°C (59°F) on average. Without this natural content temperatures would be around –15°C (5°F) and human life on earth would be impossible.

5.6.1 Annuity method

In the annuity method, non-periodic and periodic payments with changing amounts are transformed into periodic constant payments over a considered period. The annuity is this periodic constant amount, and is made up of the interest and repayment portions for the repayment of the capital used. This method of calculation permits the types of payment arising in various periods to be added directly. For example, interest and repayments for the investment are transformed with the help of the annuity factor a into average payments over a considered period T.

The payments are divided into two categories according to their temporal requirements: one-off or non-periodic payments, and regular payments. The individual costs are summarized under the general terms capital-related, consumption-related and operation-related. The considered period is taken as the service life of the short-lived and/or the more capital-intensive system components, so that the residual value has to be determined for the remaining system components. For solar energy systems consideration of the system as a whole has become the norm. After the considered period expires the whole system is regarded as being written off; no residual value is set.

The following types of costs are to be considered:

- capital-related costs, such as interest and repayments as well as servicing costs
- consumption-related costs: costs for the auxiliary energy (electricity for the pump)
- operation-related costs, such as insurance costs.

5.6.1.1 GENERAL PROCEDURE

For all types of costs the annuities are separately determined and added together:

$$AN_{\text{tot}} = AN_{\text{c}} + AN_{\text{s}} + AN_{\text{o}}$$

where AN_{tot} is the total annuity, AN_{c} is the annuity for capital-related costs, AN_{s} is the annuity for consumption-related costs, and AN_{o} is the annuity for operation-related costs.

The annuity for capital-related payments is given by

$$AN_{\text{c}} = A_0\,(1 - \text{R})a + f_{\text{k}}A_0 ba_{\text{SER}} = AN_{\text{i}} + AN_{\text{SER}}$$

where AN_{c} is the annuity for capital-related payments (= €/a or \$/a or £/a); AN_{i} is the annuity for investment-related payments (€/a or \$/a or £/a) = $A_0(1 - R)a$; AN_{SER} is the annuity for servicing payments = $f_{\text{k}}A_0 ba_{\text{SER}}$; A_0 is the procurement costs for the system;

$$a = \frac{q^T\,(q - 1)}{q^T - 1} = a(q, T)$$

T is the period considered in a (a = years, latin: annus); q is an interest factor which = $1 + (p/100)$, p is the interest (%); f_{s} is a factor for establishing the service costs in %/year of investment amount without grant; ba_{SER} is a price-dependent annuity factor for servicing payments = $b(T, q, r_{\text{s}}) \times a(q, T)$, and $b(T, q_s, r_{\text{k}})$ is a cash value factor; r_{s} is the annual price change factor for servicing payments; and R is a component-specific residual value factor. The residual value is usually set to zero for solar systems.

The annuity for consumption-related payments is given by

$$AN_{\text{c}} = A_{\text{c1}} ba_{\text{c}}$$

5.6.2 Types of costs for solar energy systems

The following general conditions apply to the individual types of costs in solar systems.

The considered period for the annuity calculation is normally 20 years for solar systems. This figure is often seen as too conservative, as the main cost component (the collector field) can easily have a service life of 30 years. Individual considerations are thus often carried out with time spans of 25 and 30 years. Interest rates are always changing, but an interest rate of $p = 6\%$ has been used for the above calculation.

(see Figure 5.18).

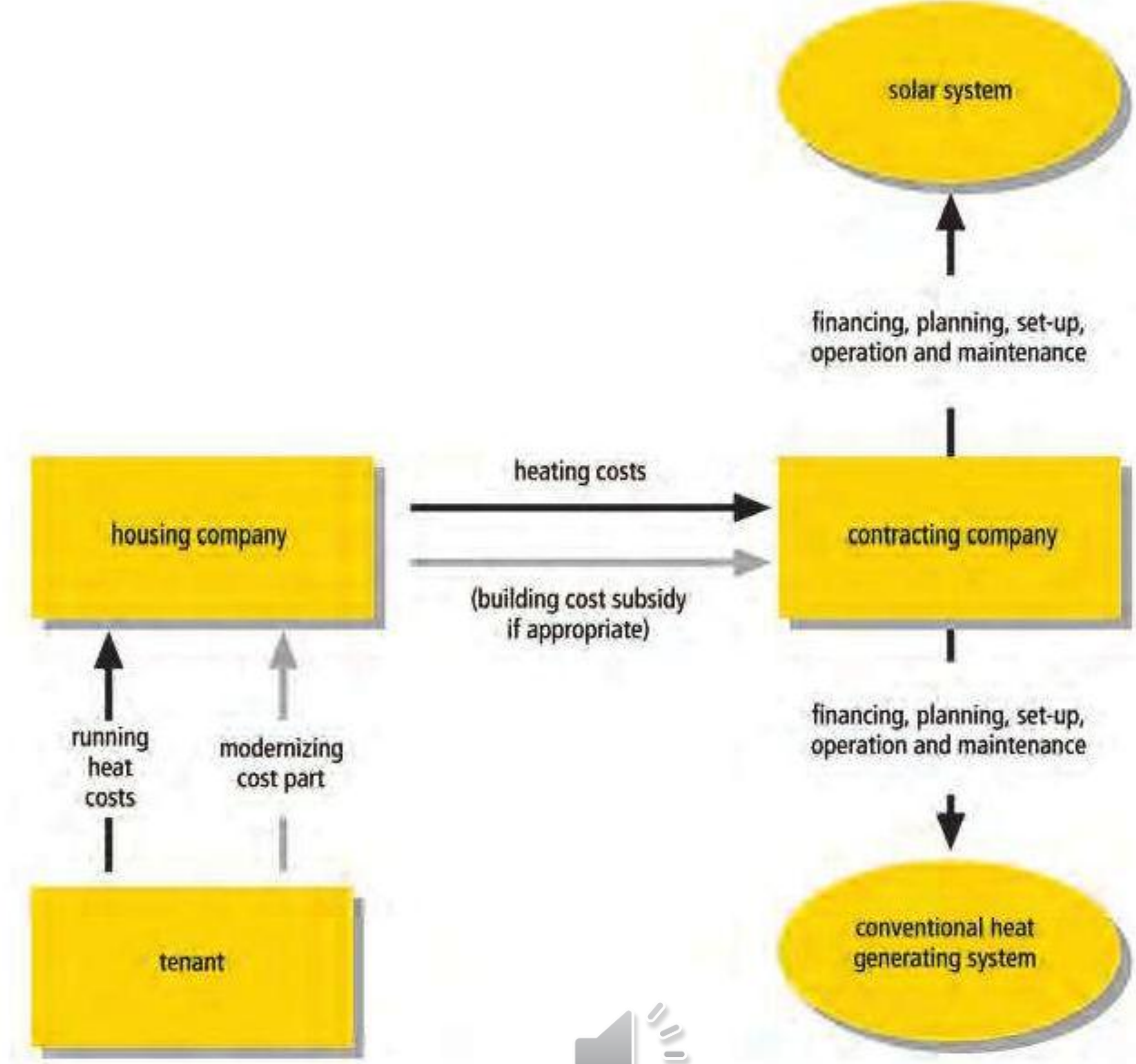
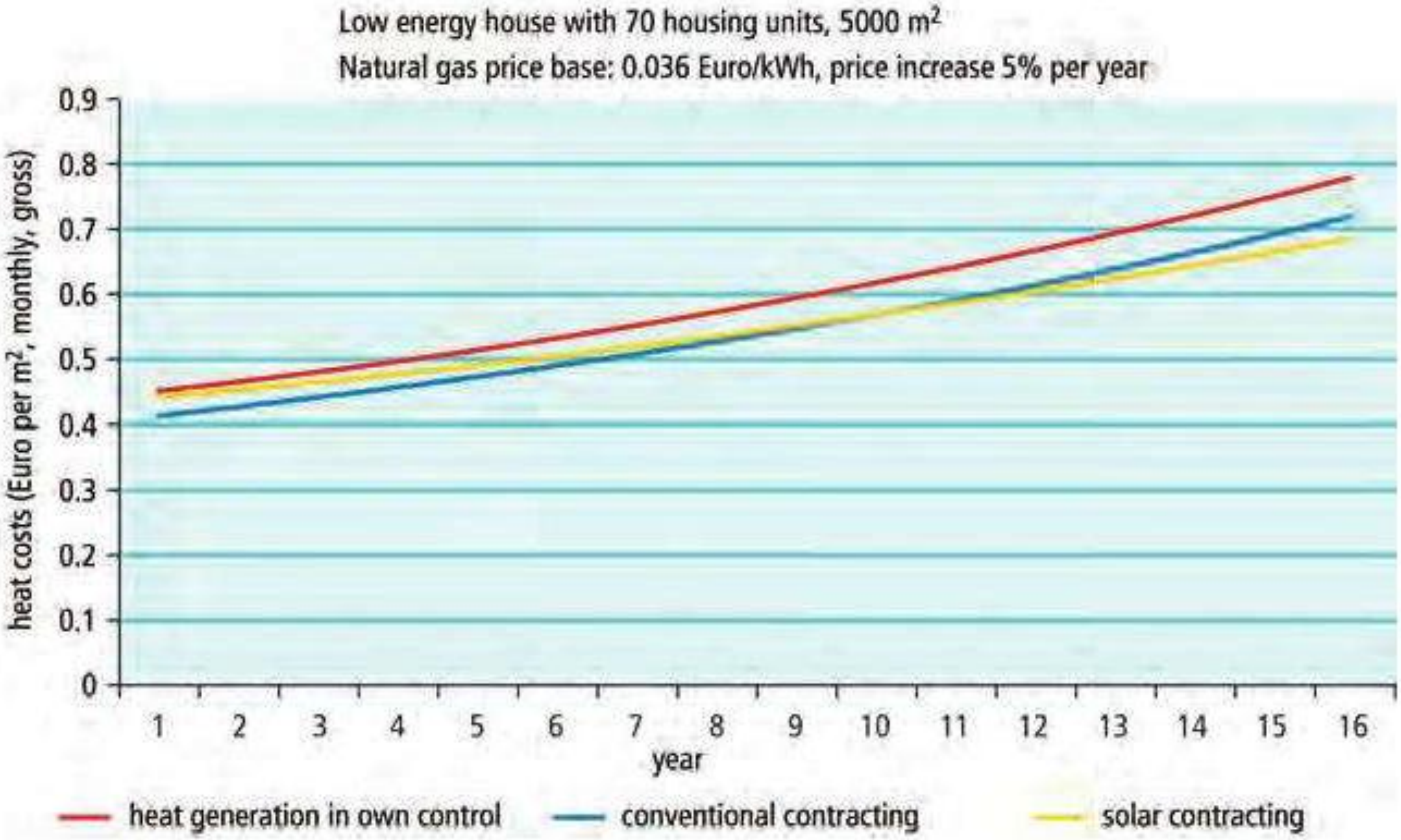


Figure 5.18.
Heat supply model, solar contracting



Low energy house with 70 housing units, 5000 m²

Natural gas price base: 0.036 Euro/kWh, price increase 5% per year

The concept of solar-supported district heating systems has come into consideration mainly in connection with the building of new housing estates or large building complexes that have been designed as low-energy buildings, as an environmentally friendly supply variant. It is important in such projects that, from the outset, the best possible technical preconditions are created for the use of solar energy by means of integrated energy planning. These include:

- a plan of the development with the orientation of the buildings that are favourable for active and passive use of solar energy (south alignment)
- planning of the estate or buildings according to solar architectonic criteria
- increased thermal protection in the buildings (low-energy building method)
- low-temperature heating systems, which permit a low network return temperature and hence a higher solar yield
- central heating plants and storage tanks arranged centrally to minimize distribution losses
- sufficient space for the heat storage tank.

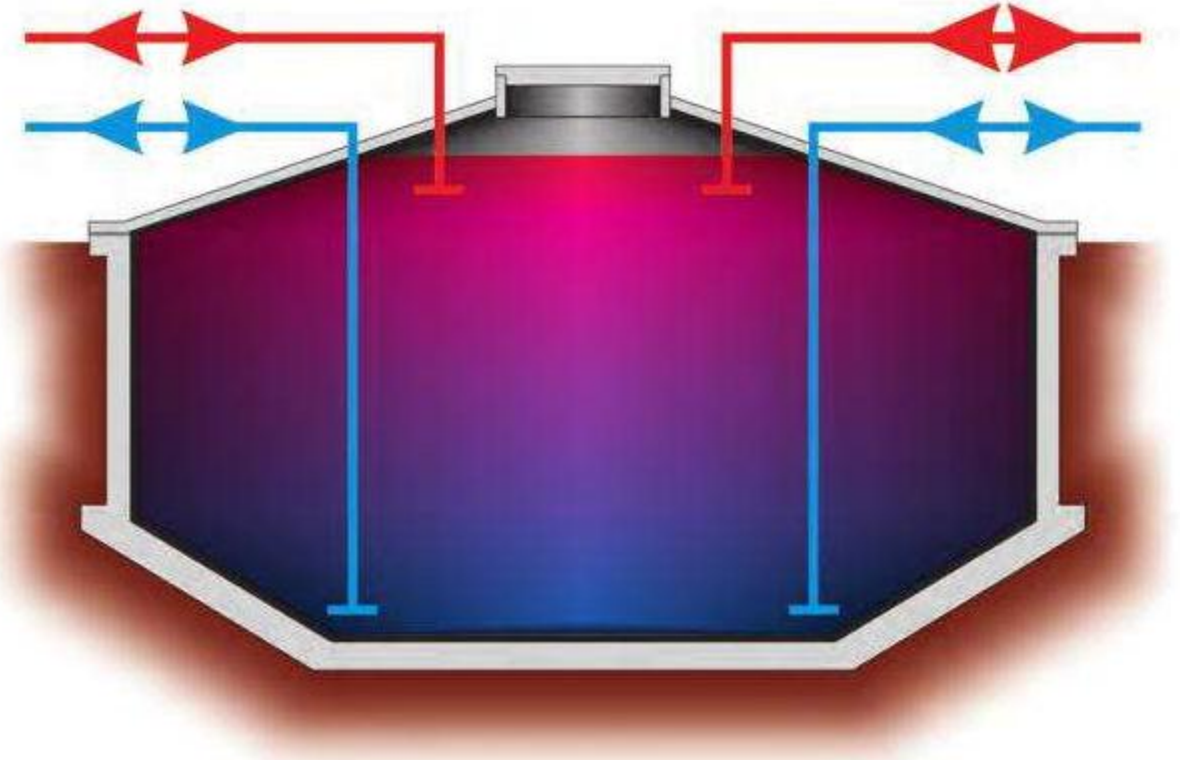
5.8.4 Components of solar district heating systems

5.8.4.1 STORAGE TANKS

As short-term storage tanks, either steel buffer tanks in the standard sizes (up to 6 m^3; 212 ft^3), in which the desired total volume can be achieved by connecting several individual tanks in succession, are used, or special custom-made designs are arranged. Different principles are used in the selection of long-term heat storage systems.

EARTH RESERVOIRS

This storage system is designed as a concrete container that is either partially or completely submerged in the earth. It is lined to seal it against vapour diffusion, and is thermally insulated. The storage medium is water (Figure 5.21).

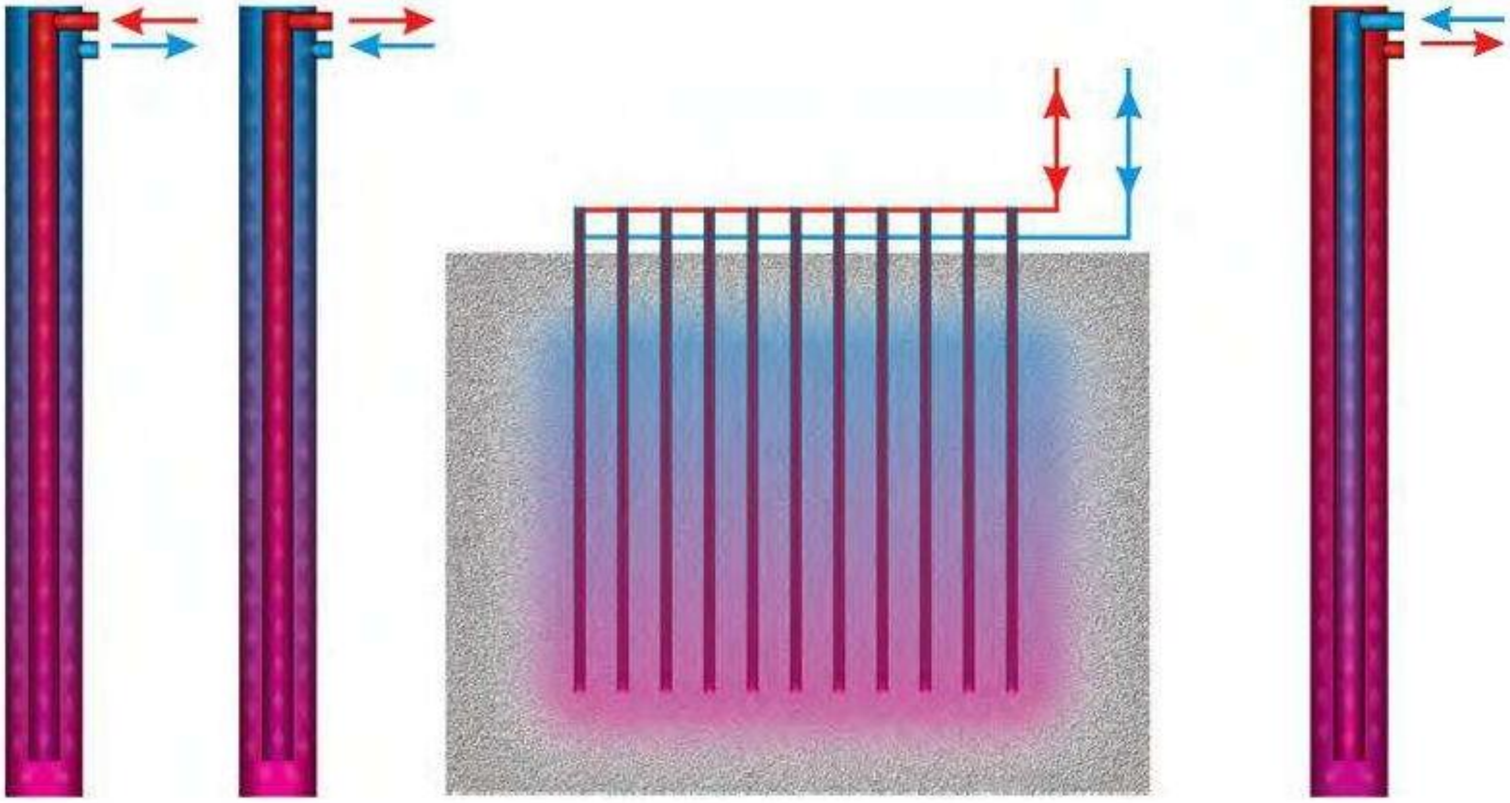


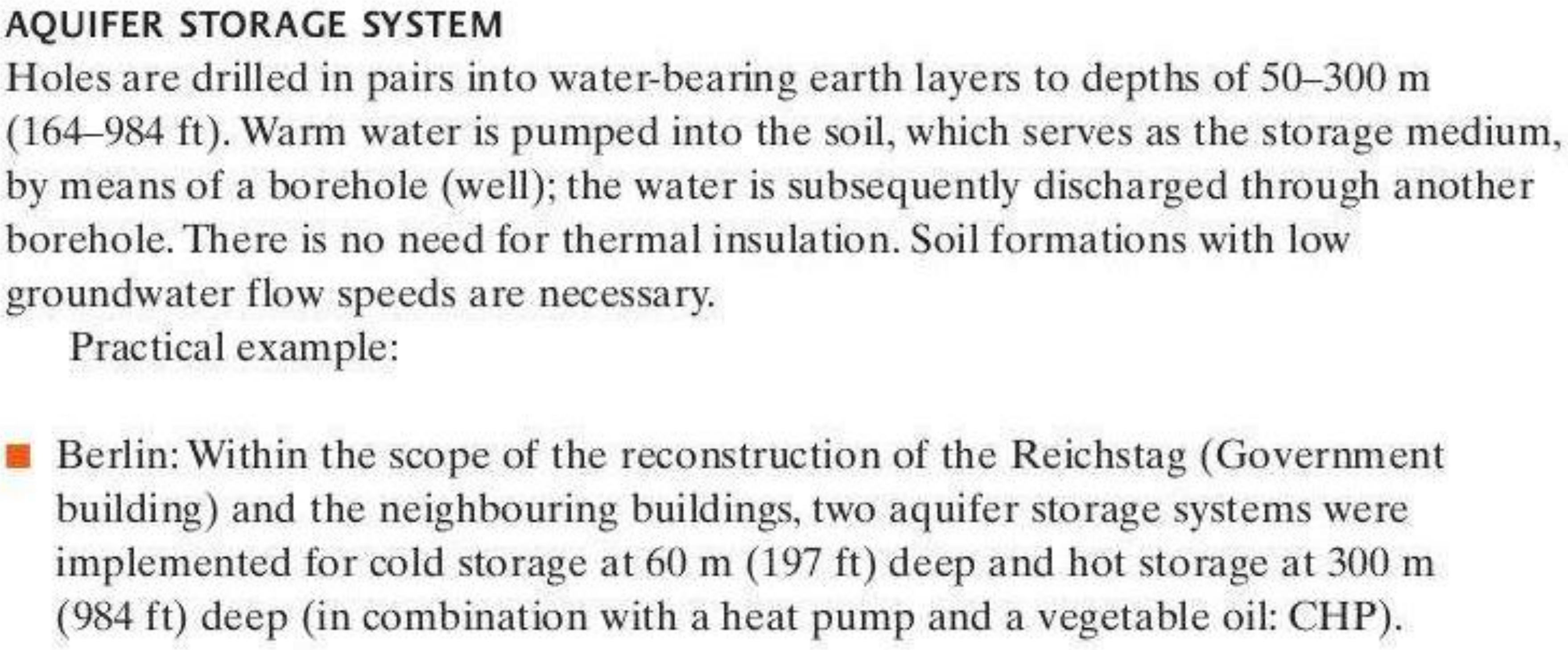
EARTH PROBE STORAGE SYSTEM

For this type of storage system, heat exchanger pipes are laid horizontally in the earth or vertically into drilled holes (U-tube probes), and are thermally insulated up to the surface. The surrounding soil is used directly as the storage medium, and heats up or cools down. Practically any size of storage volume is possible. The soil characteristics however, play an important role (Figure 5.22).

Practical examples:

- Neckarsulm: Storage volume around 175,000 m³ (6,180,067 ft³).
- Arnstein: Approximately 3000 m³ (105,944 ft³) storage volume; utilization about 36%.





AQUIFER STORAGE SYSTEM

Holes are drilled in pairs into water-bearing earth layers to depths of 50–300 m (164–984 ft). Warm water is pumped into the soil, which serves as the storage medium, by means of a borehole (well); the water is subsequently discharged through another borehole. There is no need for thermal insulation. Soil formations with low groundwater flow speeds are necessary.

Practical example:

- Berlin: Within the scope of the reconstruction of the Reichstag (Government building) and the neighbouring buildings, two aquifer storage systems were implemented for cold storage at 60 m (197 ft) deep and hot storage at 300 m (984 ft) deep (in combination with a heat pump and a vegetable oil: CHP).

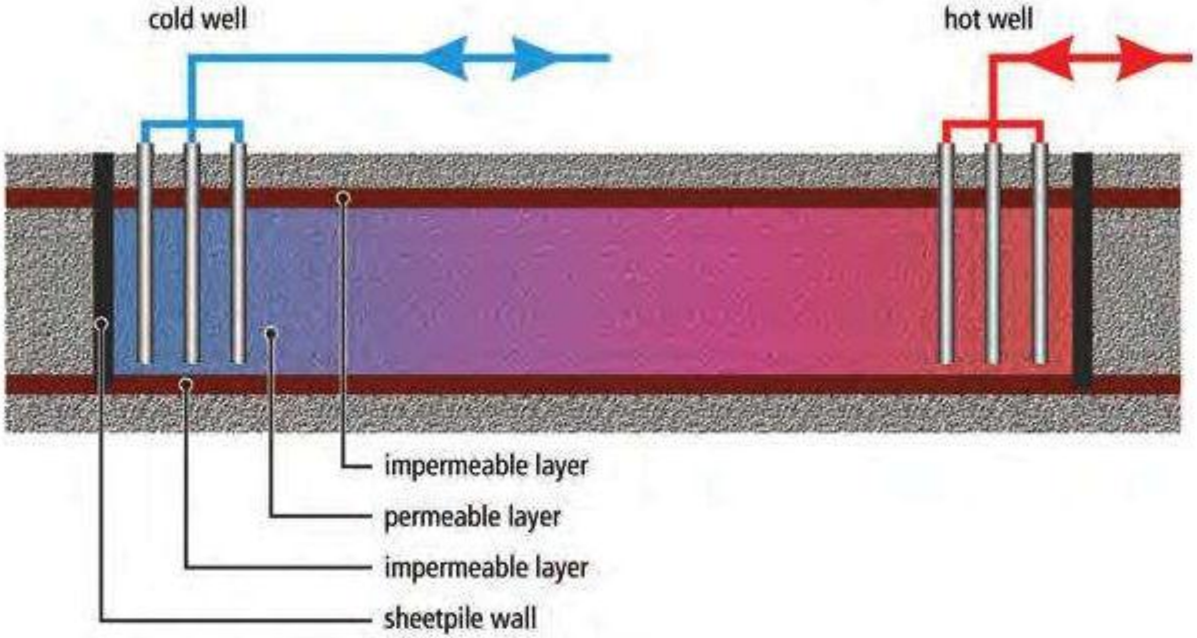


Figure 5.23.
Aquifer storage system

- *2+2 conductor network*. This comprises two conductor lines for the heat supply to the buildings (domestic water heating takes place locally in the individual buildings), and an additional two conductor lines for the solar circuit.
- *4+2 conductor network*. This comprises four conductor lines for the heat supply: two lines each for domestic hot water (DHW) and space heating, plus an additional 2 lines for the solar. It permits central domestic water heating, but results in higher circulation losses.
- *3 conductor line network (two variants)*. An (older) variant uses a separate supply for the space heating and water heating together with a common return. In connection with solar district heating a system supply, a common return and a solar supply are now frequently used (newer variant).