Planning and Installing

Solar Thermal Systems

A guide for installers, architects and engineers

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Contents

1 Solar radiation and arguments for its use

1.1 Solar radiation

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 143 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 a quarter of an hour than the human race uses in a whole year.*

The age of the sun is estimated by astrophysicists to be about 5 billion years. With a total life expectation of 10 billion years the sun will be available as an energy source for another 5 billion years. Hence from our human perspective the sun offers an unlimited life.

Figure 1.1.
The sun: basis of all life on earth

1.1.2 Astronomical and meteorological bases

On the outer edge of the earth's atmosphere the irradiated power of the sun is virtually constant. This irradiated power or radiation intensity falling on an area of one square metre is described as the *solar constant*. This constant is subject to small variations influenced both by changes in the sun's activity (sunspots) and by differences in the distance between the earth and the sun. These irregularities are mostly found in the ultraviolet range: they are less than 5%, and hence not significant in application of the solar constant for solar technology. The average value of the solar constant is given as I_0 = 1.367 W/m^2 (watts per square metre).

Even based on the astronomical facts alone, the amount of solar energy available on the earth is very variable. It depends not only on the geographical latitude, but also on the time of day and year at a given location. Because of the inclination of the

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. 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/m²)
Heat quantity,	Q (Wh, kWh)

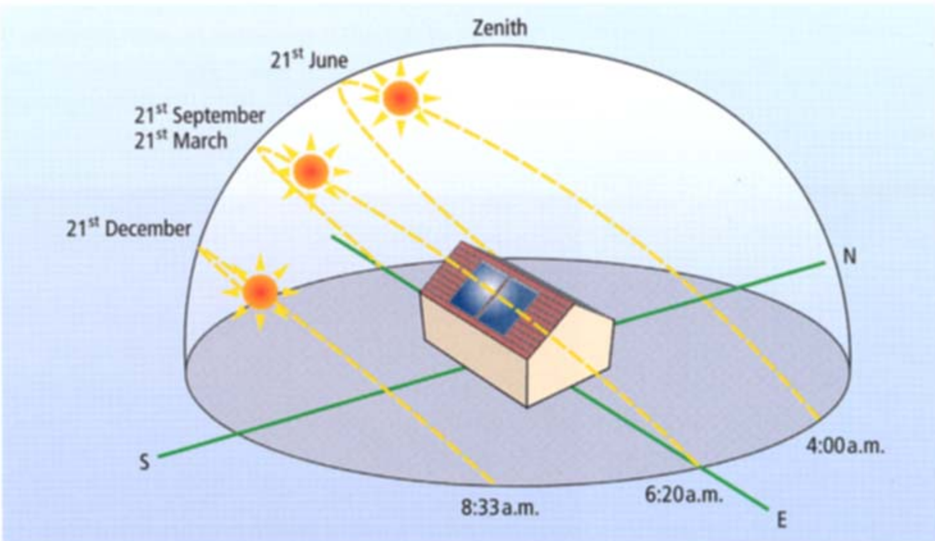


Figure 1.2. The sun's path at different times of the year at central European latitude (London, Berlin)

earth's axis, the days in summer are longer than those in winter, and the sun reaches higher solar altitudes in the summer than in the winter period (Figure 1.2).

Figure 1.3 shows the sequence over a day of the irradiation in London on a horizontal receiving surface of 1 m² for four selected cloudless days over the year. It is clear from the graph that the supply of solar radiation, even without the influence of the weather or clouds, varies by a factor of about 10 between summer and winter in London. At lower latitudes this effect decreases in strength, but at higher latitudes it can be even more pronounced. In the southern hemisphere the winter has the highest irradiations, as shown in Figure 1.4, which shows the sequence over a day of the irradiation in Sydney on a horizontal receiving surface of 1 m² on three average days over the year.

Even when the sky is clear and cloudless part of the sun's radiation comes from 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_{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_{dir}. The sum of direct and diffuse radiation is known as *global solar irradiance*, G_G (Figure 1.5).

$$G_G = G_{dir} + G_{dif}$$

Unless nothing else is given, this always refers to the irradiation onto a horizontal receiving surface.[1]

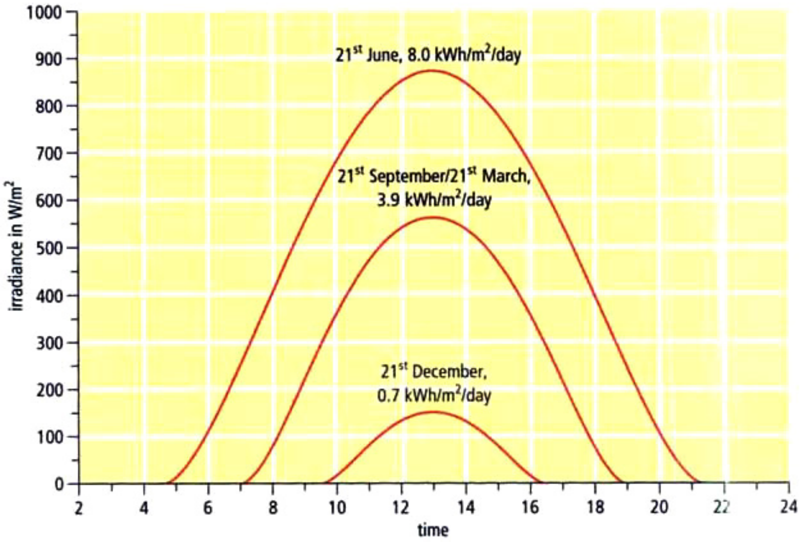


Figure 1.3. Daily courses and daily totals for irradiation in London

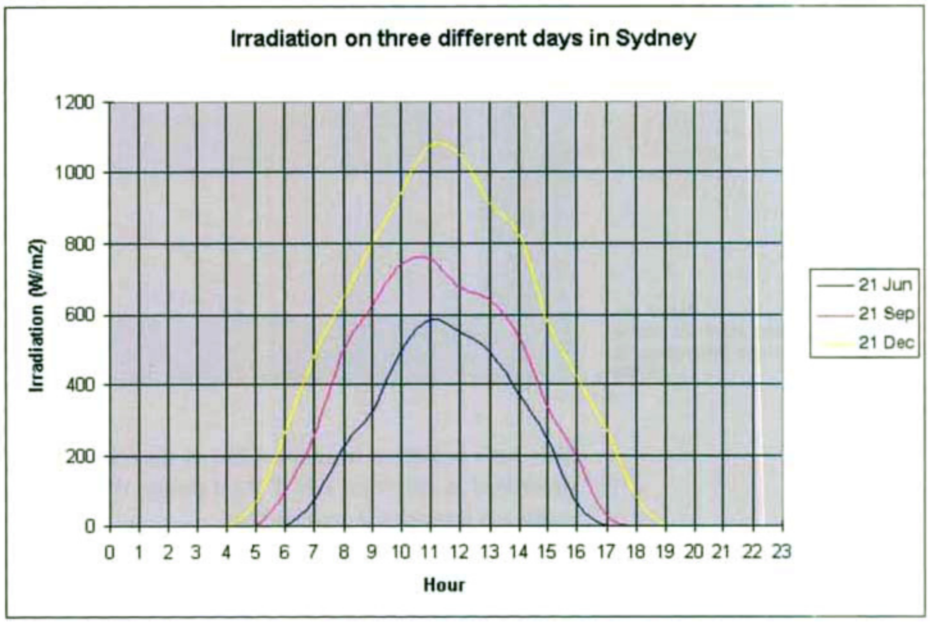


Figure 1.4. Irradiation on three different days in Sydney, Australia

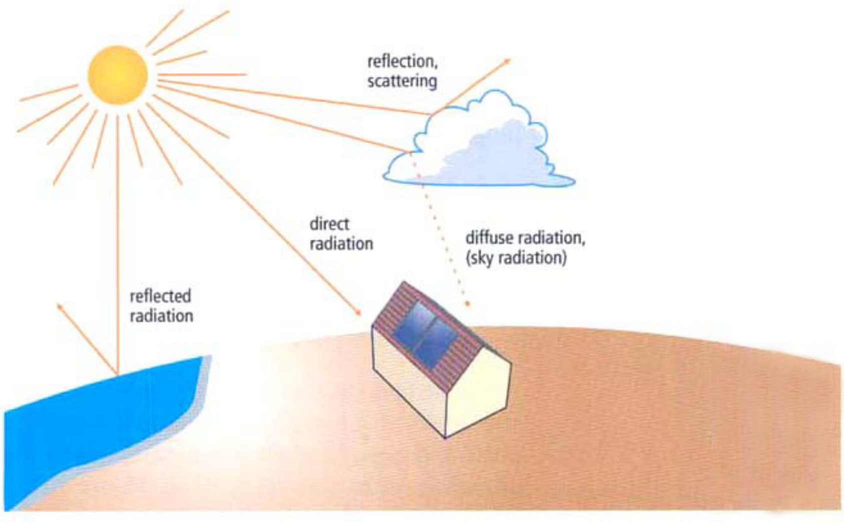


Figure 1.5. Global solar irradiance and its components

When the sun is vertically above a location the sunlight takes the shortest path through the atmosphere. However, if the sun is at a lower angle then the path through the atmosphere is longer. This causes increased absorption and scattering of the solar radiation and hence a lower radiation intensity. The *air mass factor* (*AM*) is a measure of the length of the path of the sunlight through the earth's atmosphere in terms of one atmosphere thickness. Using this definition, with the sun in the vertical position (elevation angle, $\gamma_S = 90°$), $AM = 1$.

Figure 1.6 shows the respective highest levels of the sun on certain selected days in London and Berlin. The maximum elevation angle of the sun was achieved on 21 June with $\gamma_S = 60.8°$, and corresponded to an air mass of 1.15. On 22 December the maximum elevation angle of the sun was $\gamma_S = 14.1°$, corresponding to an air mass of 4. At lower latitudes, all elevation angles will increase: for example, at a latitude of 32° (north or south), the highest elevation angle will be 80.8° and the lowest angle will be 34.1°.

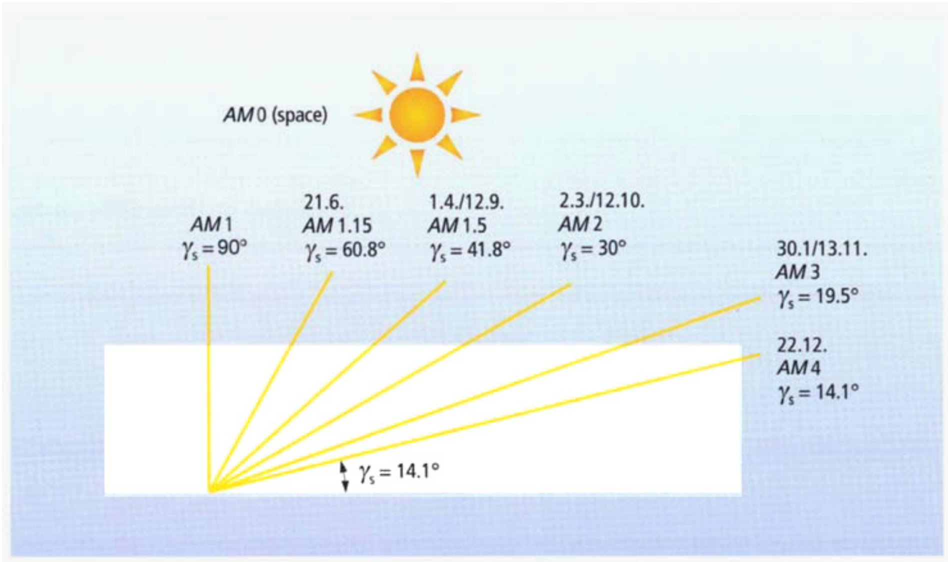


Figure 1.6.
Sun's level at midday within the course of a year in London and Berlin (latitude: 52°N)

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 (O_3, H_2O, O_2, CO_2)
- Rayleigh scattering (scattering by the air molecules)
- Mie scattering (scattering by dust particles and contamination in the air).

See Figure 1.7.

Table 1.1 shows the dependence of the irradiation on the elevation angle, γ_S. Absorption and scattering increase when the sun's elevation is lower. Scattering by dust particles in the air (Mie scattering) is heavily dependent on the location. It is at its greatest in industrial areas.

Table 1.1.
Effect of elevation angle on attenuation of irradiation

γ_S	*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

After the general astronomical conditions, the cloud cover or state of the sky is the second decisive factor that has an effect on the supply of solar radiation: both the irradiated power and the proportions of direct and diffuse radiation vary greatly according to the amount of cloud (Figure 1.8).

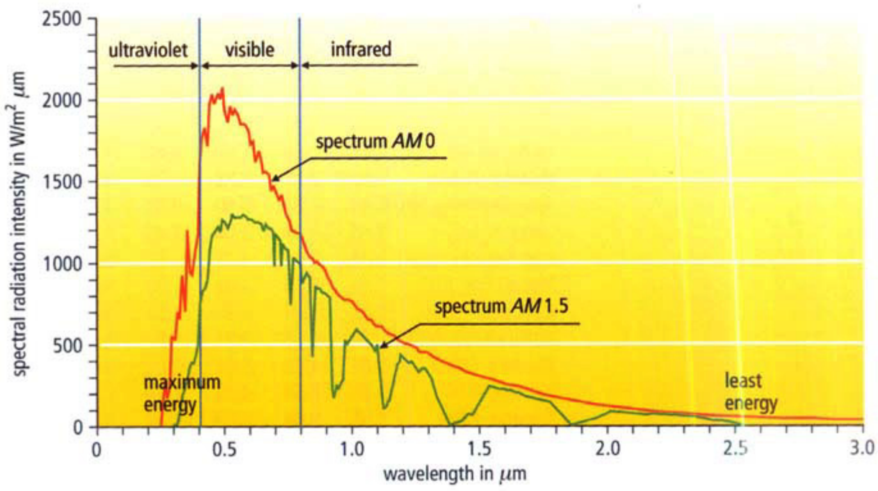


Figure 1.7.
Sun spectrum AM *0 in space and* AM *1.5 on the earth with a sun elevation of 41.8°*

Over many years the average proportion of diffuse to global solar irradiance in central Europe has been found to be between 50% and 60%. In sunnier climates the fraction of diffuse radiation is lower; in the winter months this proportion is higher. See Figure 1.9.[2]

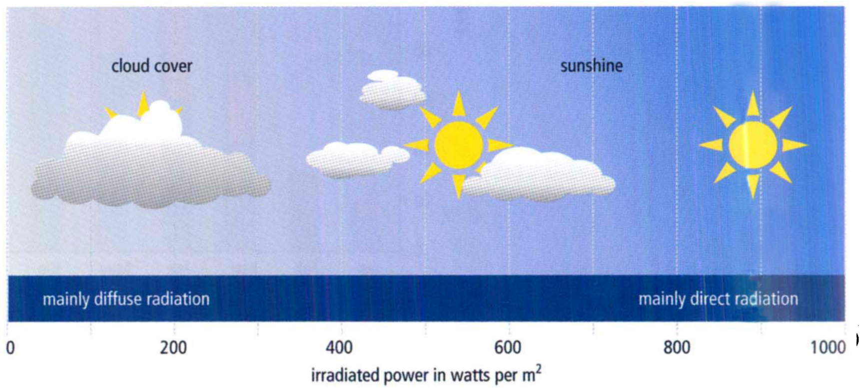


Figure 1.8.
Global solar irradiance and its components with different sky conditions

The average annual global solar irradiance is an important value for designing a solar plant. It is significantly higher at lower than at higher latitudes, but for climatological reasons severe regional differences can arise. The maps in Figure 1.10 give an indication of the solar irradiation in different regions. Table 1.2 gives an overview of the monthly solar irradiation in a number of cities around the world (measured in kWh/m^2 per day on a horizontal surface). Over the course of a year global solar irradiance is subject to significant daily variations, especially in climates where cloudiness occurs regularly.

In addition to global solar irradiance, the *sunshine duration* is sometimes given: that is, the number of hours each year for which the sun shines. In the United Kingdom this value varies between 1300 and 1900 hours per year. However, the radiation is a far more reliable figure to use when designing or installing solar energy systems.

Table 1.2. Monthly solar irradiation (kWh/m² per day) around the world

City	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Birmingham, UK	0.65	1.18	2.00	3.47	4.35	4.53	4.42	3.87	2.67	1.48	0.83	0.45
Brisbane, AUS	6.35	5.71	4.81	3.70	2.90	2.43	2.90	3.61	4.93	5.45	6.33	6.32
Chicago, USA	1.84	2.64	3.52	4.57	5.71	6.33	6.13	5.42	4.23	3.03	1.83	1.45
Dublin, IRL	0.65	1.18	2.26	3.60	4.65	4.77	4.77	3.68	2.77	1.58	0.77	0.45
Glasgow, UK	0.45	1.04	1.94	3.40	4.48	4.70	4.35	3.48	2.33	1.26	0.60	0.32
Houston, USA	2.65	3.43	4.23	5.03	5.61	6.03	5.94	5.61	4.87	4.19	3.07	2.48
Johannesburg, SA	6.94	6.61	5.90	4.80	4.35	3.97	4.26	5.10	6.13	6.45	6.57	7.03
London, UK	0.65	1.21	2.26	3.43	4.45	4.87	4.58	4.00	2.93	1.68	0.87	0.48
Los Angeles, USA	2.84	3.64	4.77	6.07	6.45	6.67	7.29	6.71	5.37	4.16	3.13	2.61
Melbourne, AUS	7.13	6.54	4.94	3.20	2.13	1.93	2.00	2.71	3.87	5.26	6.10	6.68
New York, USA	1.87	2.71	3.74	4.73	5.68	6.00	5.84	5.39	4.33	3.19	1.87	1.48
Philadelphia, USA	1.94	2.75	3.81	4.80	5.55	6.10	5.94	5.42	4.37	3.23	2.13	1.68
Phoenix, USA	3.29	4.36	5.61	7.23	8.00	8.17	7.39	6.87	5.97	4.84	3.57	2.97
Sydney, AUS	6.03	5.54	4.23	3.07	2.61	2.33	2.55	3.55	4.63	5.87	6.50	6.13
Toronto, CAN	1.58	2.54	3.55	4.63	5.77	6.30	6.29	5.45	4.03	2.68	1.37	1.16
Vancouver, CAN	0.84	1.75	3.00	4.27	6.03	6.50	6.52	5.42	3.80	2.06	1.03	0.65

Figure 1.9. Monthly sum of global solar irradiance (diffuse and direct)

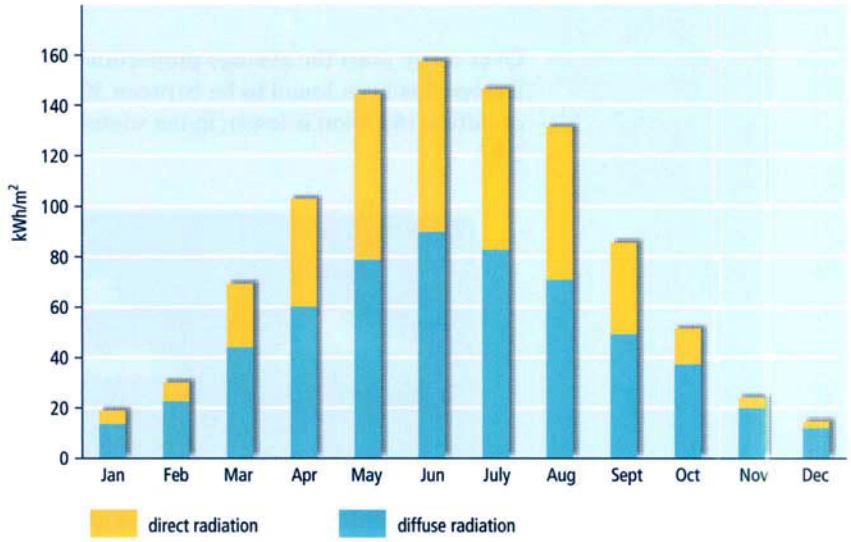


Figure 1.9a. Berlin, Germany

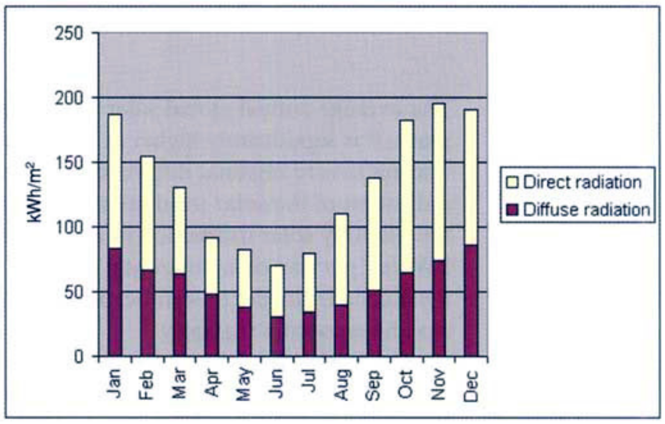


Figure 1.9b. Sydney, Australia

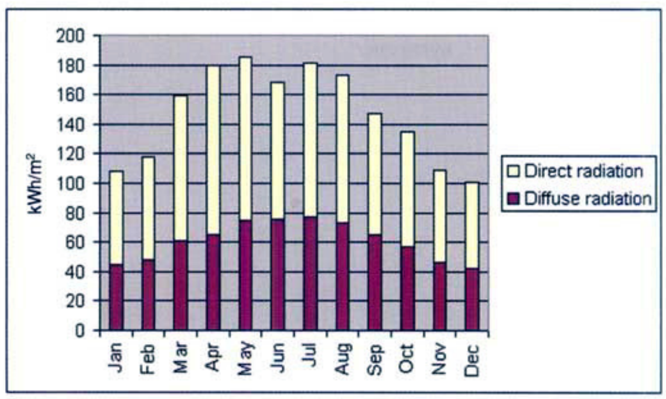
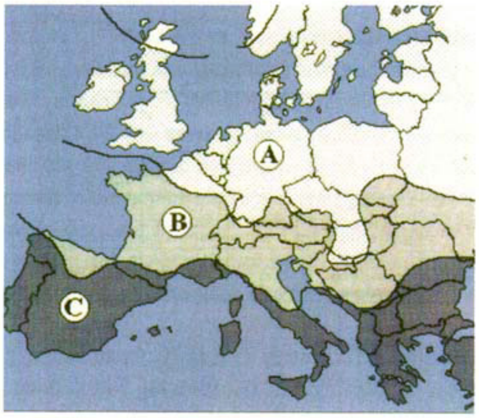


Figure 1.9c. Miami, USA

Figure 1.10.
Total annual global radiation (on horizontal surface)



Zone (see map above)	Average solar radiation on collector surface [kWh/m² day]	Solar system heat yield [kWh/m²y]
A	2.4 to 3.4	300 to 450
B	3.4 to 4.4	400 to 550
C	4.4 to 5.4	500 to 650

Figure 1.10a.
Europe

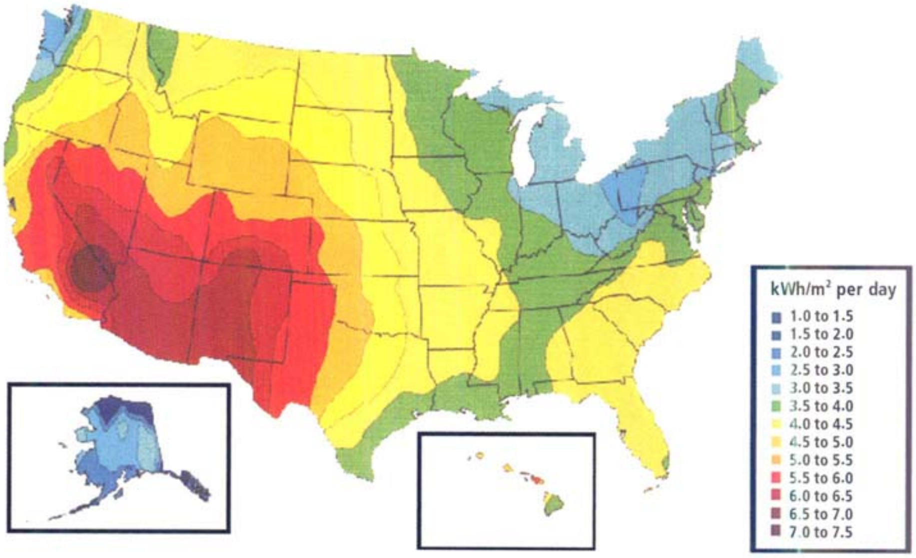


Figure 1.10b.
USA

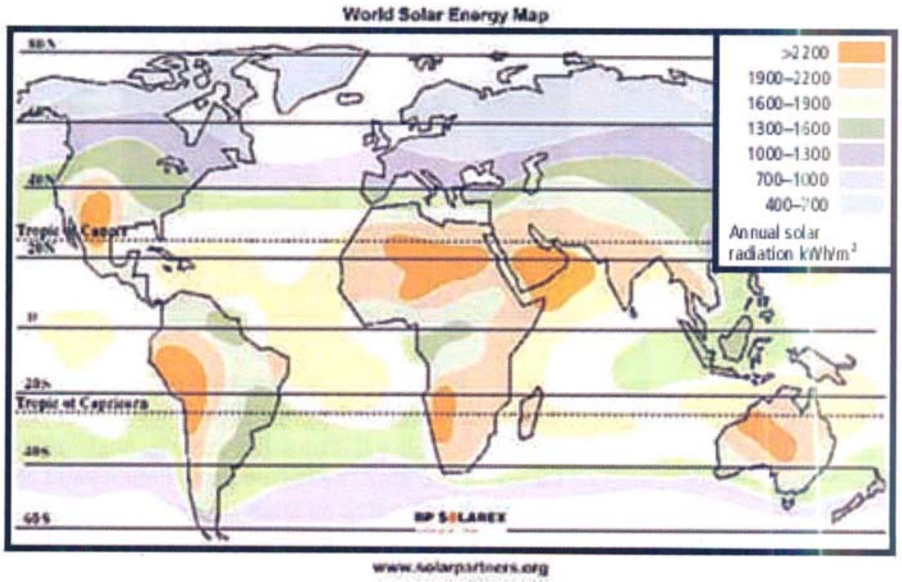


Figure 1.10c.
The world

Next Page

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

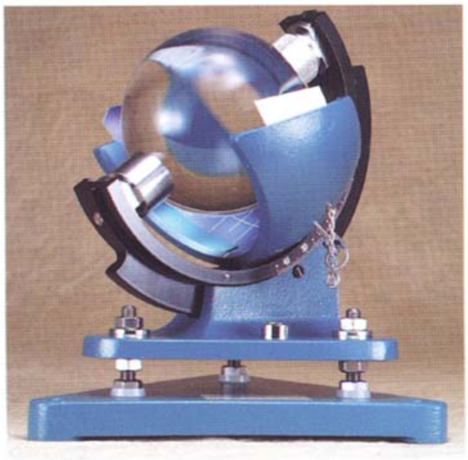


Figure 1.12 (left). MacSolar

Figure 1.13 (right). Campbell–Stokes sunshine recorder

1.1.3 Influence of orientation and tilt angle

The variables or figures that have been given so far referred to a horizontal receiving surface, such as a flat roof. Because the angle of incidence of the sun varies over the course of the year, the maximum radiation yield can be obtained only if the receiving surface is inclined at an angle to the horizontal. The optimum angle of inclination is larger in the low-radiation months than in the summer because of the low elevation of the sun.

2 Components of solar thermal systems

2.1 How does a solar thermal system work?

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).

In central and northern Europe, as well as in the USA, Canada and other countries, thermal solar systems operate with a water–glycol mixture that is circulated in a closed circuit (forced circulation). This system, which has a solar circuit separated from the domestic water circuit, is called an *indirect system* (see Figure 2.1). In some countries systems also exist with pure water as the heat transfer medium (for instance the so-called *drainback systems*) or with direct circulation of the domestic water through the collector.

The controller will only start the solar circuit pump when the temperature in the collector is a few degrees above the temperature in the lower area of the store. In this way the heat transfer liquid in the collector – having been warmed by the sun – is

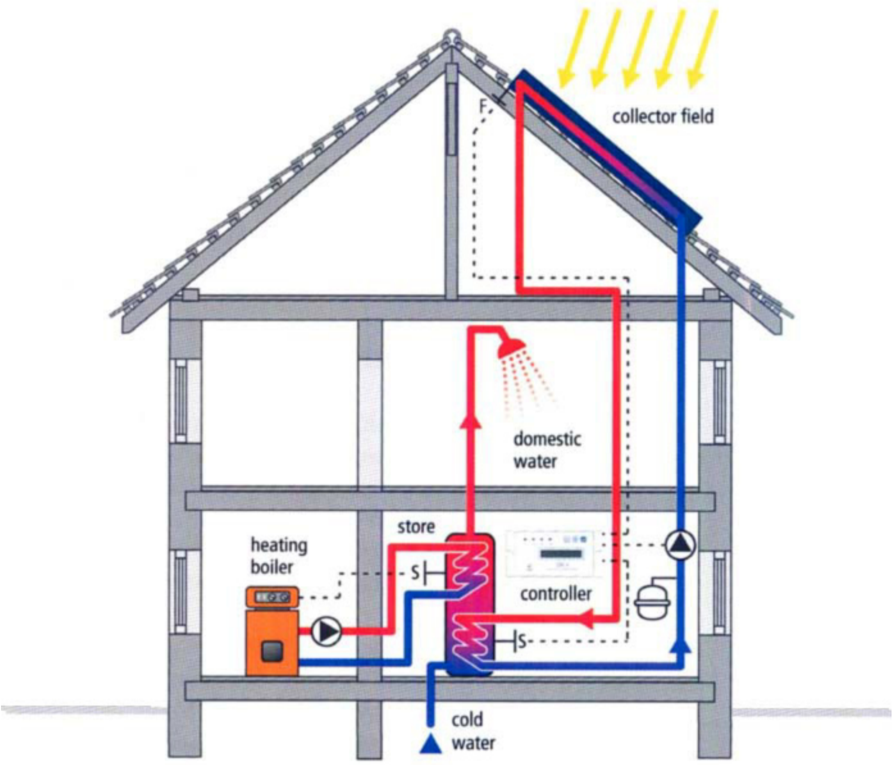


Figure 2.1. Standard solar water heating system with heating boiler for additional heating (S = temperature sensor)

transferred into the lower heat exchanger, where the heat is transferred to the stored domestic water.

In Australia, Israel and other Mediterranean countries, as well as many other countries, especially with tropical or subtropical climates, systems are designed based on the principle that hot water rises. These are called *thermosyphon* systems, and the storage tank is almost always located outdoors, directly on top of the solar collector; see Figure 2.2.

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 m^2 of collector surface per person and approximately 40–60 l 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, 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.

The individual components of thermal solar systems are introduced in the following sections.

2.2 Collectors

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.

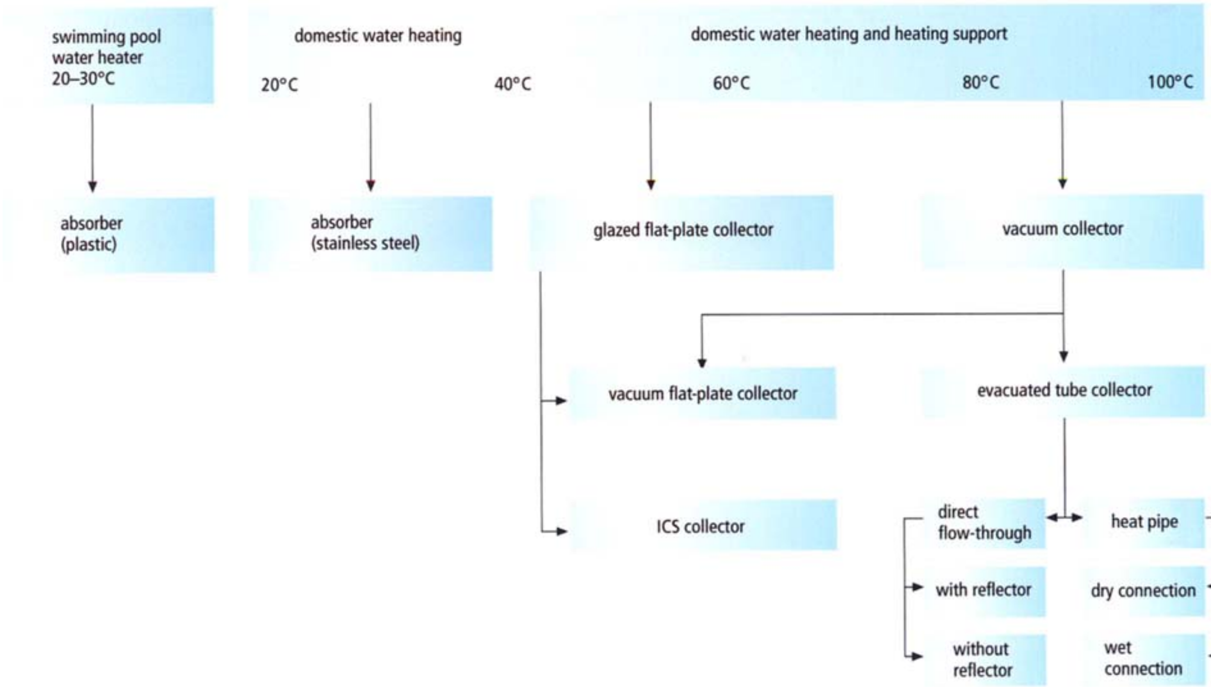


Figure 2.3.
Overview of types of collector

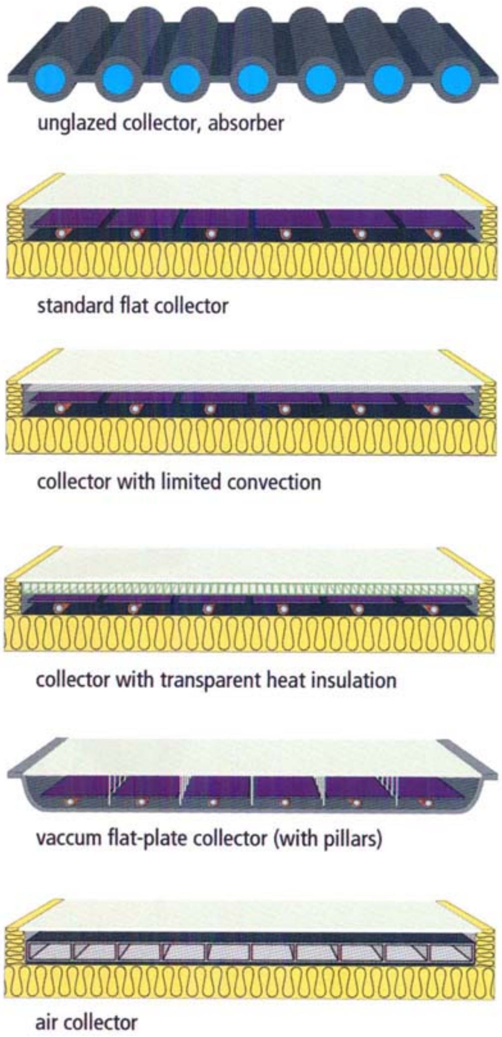


Figure 2.4.
Different collector designs

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

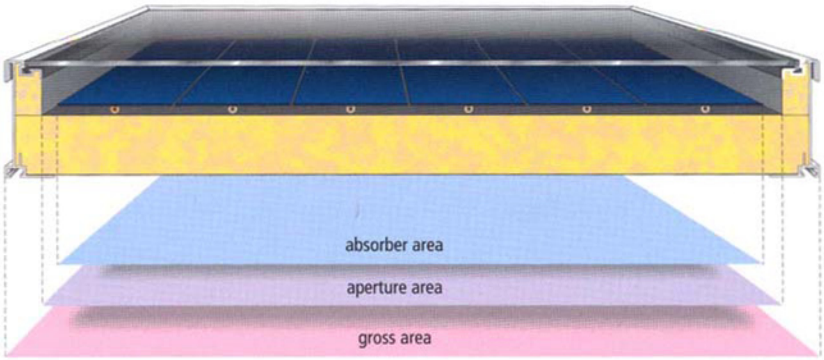


Figure 2.5.
Cross-section of a flat-plate collector with description of the different areas

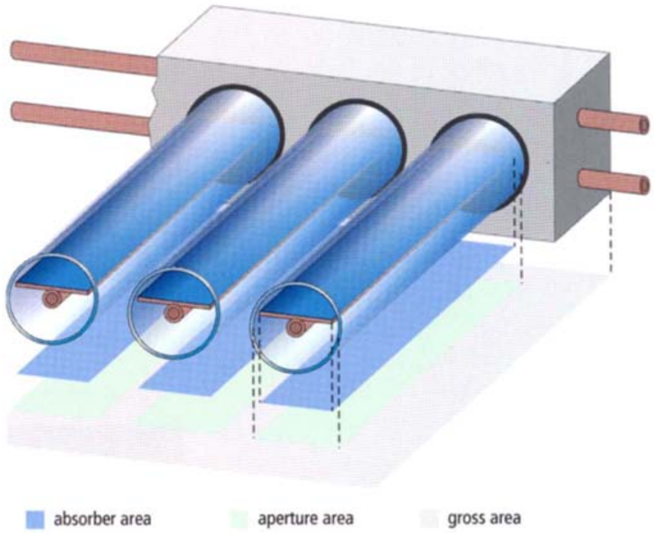


Figure 2.6.
Cross-section of a heat-pipe evacuated tube collector with description of the different surface areas

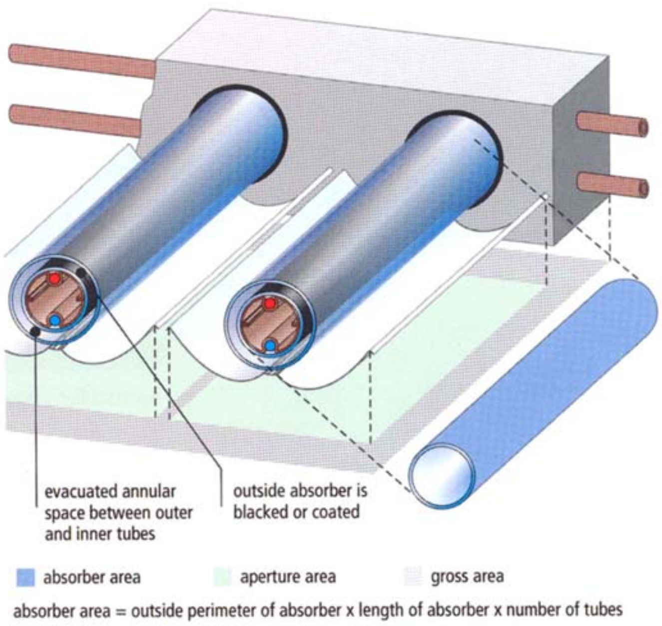


Figure 2.7.
Cross-section of a double evacuated tube collector ('Sydney tubes') with description of the different surface areas

When comparing collectors, the *reference area* is important – that is, the surface area from which the collector's characteristic values are drawn. In the collector test methods according to EN 12975 the reference area is equal to either the aperture area or the absorber area.

For the energy yield, it is not the collector (gross) area that is crucial but the absorber area. (The exception to this is evacuated tube collectors with reflectors (see section 2.2.3). In this case the receiving area – that is, the aperture area – is crucial. The radiation that impinges on this area is reflected to the absorber.)

2.2.1 Unglazed collectors

The simplest kind of solar collectors are unglazed collectors. These have no glazing or insulated collector box, so that they consist only of an absorber (see also section 2.2.2). Unglazed collectors can be found in various application areas, but they are used mainly as a plastic absorber for heating swimming pool water (see Chapter 7). They are also sometimes found as a selectively coated stainless steel absorber for preheating domestic water. This collector has a lower performance at equal operating temperature than a glazed flat-plate collector as it lacks the glass cover, housing and thermal insulation. It therefore has higher thermal losses and can be used only at very low operating temperatures, but because of its simple construction it is inexpensive. See Table 2.1.

Table 2.1. Comparison of yields and cost for stainless steel absorber and flat-plate collector[a]

	Yield (kWh/m²)	Cost (€ or US$ per m²)	Cost (£ per m²)
Unglazed stainless steel absorber	250–300	140–160	98–112
Flat-plate collector	350–500	200–350	140–245

[a]Not including fixing, mounting and VAT

Advantages of the unglazed collector:

- The absorber can replace the roof skin, saving a zinc sheeting, for example. This leads to better heat prices through reduced costs.
- It is suitable for a diversity of roof forms, including flat roofs, pitched roofs and vaulted roofs. It can easily be adapted to slight curves.
- It can be a more aesthetic solution for sheet metal roofs than glazed collectors.

Disadvantages:

- Because of the lower specific performance, it requires more surface area than a flat collector.
- Because of the higher heat losses, the temperature increase (above the air temperature) is limited.

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.

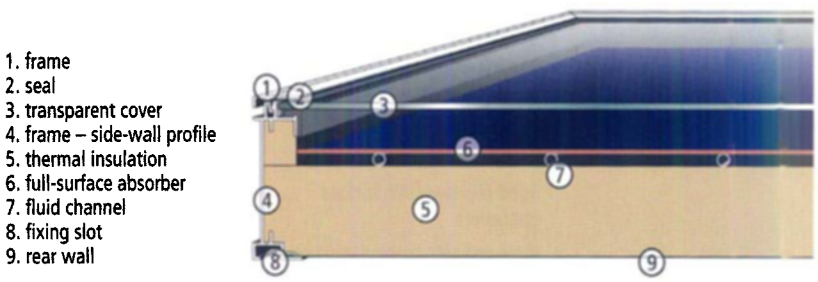


Figure 2.8. Section through a glazed flat-plate collector

Without the glass cover, glazed flat-plate collectors weigh between 8 and 12 kg per m^2 of collector area; the glass cover weighs between 15 and 20 kg/m^2. These collectors are made in various sizes from 1 m^2 to 12.5 m^2, or larger in some cases.

ABSORBER

The core piece of a glazed flat-plate collector is the *absorber*. This consists of a heat-conducting 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.

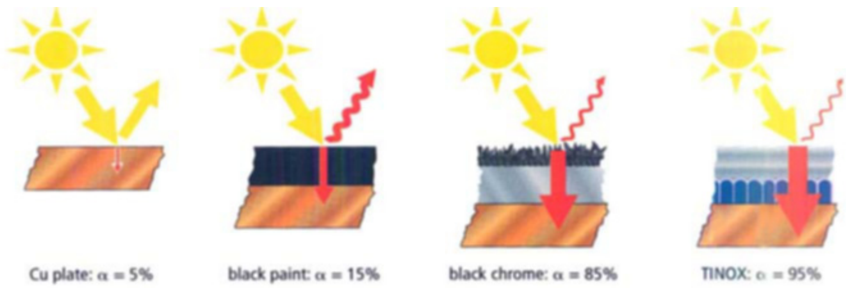


Figure 2.9. Absorption and emission behaviour of different surfaces

Most spectral-selective layers have an absorption rate of 90–95%, and an emission rate of 5–15%. Commonly used selective coatings consist of black chrome or black nickel. See Table 2.2. However, the latest developments in selective coatings with improved optical characteristics currently offered on the market have been applied either in a vacuum process or by sputtering. These processes feature a significantly lower energy consumption and lower environmental load during manufacturing in comparison with black-nickel and black-chrome coatings, which are usually applied by electroplating. In addition, the energy gain of these absorbers is higher at higher temperatures or at low levels of solar irradiance than that of absorbers with black-chrome or black-nickel coatings.[8]

Table 2.2. Advantages and disadvantages of various absorber types

Type	Advantage	Disadvantage
Roll-bonded absorber	Good thermal properties, no mixed materials; simplifies subsequent recycling	Subject to corrosion of aluminium in connection with copper tube
Absorber strips with pressed-in copper tube	High flexibility in size; cheap because of greater volume of production	Many solder points
Absorber with tube system pressed in between metal sheets	No mixed materials; simplifies subsequent recycling	High production cost as connection possible only on plain metal sheet
Absorber with soldered-on tube system	Very flexible in size and flow rate	Heat transfer not optimal
Full flow-through stainless steel absorber	Good heat transfer to liquid	High weight, thermal inertia
Serpentine absorber	Only two solder points in tube system	Higher pressure loss than tube register
Tube register (full-surface absorber)	Lower pressure loss than serpentine absorber	Many solder points in tube system; expensive
Tube register (vane absorber)	Lower pressure loss than serpentine absorber	Many solder points in tube system

RADIATION AND INTERACTION WITH MATTER

When short-wave sunlight (wavelength 0.3–3.0 μm) 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 μm) and radiated according to the surface structure.

These processes are described physically as the degrees of reflection, absorption, transmission and emissivity of a body.

- *degree of reflection*, ρ:

$$\rho = \frac{\text{Reflected radiation}}{\text{Incident radiation}}$$

- *degree of absorption* (absorption coefficient), α:

$$\alpha = \frac{\text{Absorbed radiation}}{\text{Incident radiation}}$$

- *degree of transmission*, τ:

$$\tau = \frac{\text{Transmitted radiation}}{\text{Incident radiation}}$$

- *emissivity*, ϵ:

$$\epsilon = \frac{\text{Emitted radiation}}{\text{Absorbed radiation}}$$

The variables ρ, α, τ and ϵ are dependent on the material and wavelength. The sum of ρ, α and τ is equal to 1 (100%).

For solar thermal technology the *Stefan–Boltzmann law* is significant. This says that a body emits radiation corresponding to the fourth power of its temperature.

$$\dot{Q} = \sigma T^4$$

where $\dot{Q}$ is the emitted thermal radiation (W/m^2), σ is the Stefan–Boltzmann constant = 5.67×10^{-8} (W/m^{2}K^4), and T is the absolute body temperature (K).

In order to reduce the emissions and hence increase the efficiency of the collectors, new absorber coatings are being developed continuously.

As a material for the absorber plate, copper possesses the requisite good thermal conduction. The thermal transmission between absorber plate and tube takes place through the best possible heat-conducting connection.

A further factor for a large energy yield is a low heat capacity, which permits a fast reaction to the ever-changing level of solar radiation. For absorbers with flow channels this is lower (0.4–0.6 l of heat transfer liquid per m^2 of absorber surface) than for full-surface flow absorbers, such as for example cushion absorbers with 1–2 l/m^2.

INSULATION

To reduce heat losses to the environment by thermal conduction, the back and edges of the collector are heat insulated.

As maximum temperatures of 150–200°C (when idle) are possible, mineral fibre insulation is the most suitable here. It is necessary to take account of the adhesive used. This must not vaporize at the temperatures given, otherwise it could precipitate onto the glass pane and impair the light-transmitting capacity.

Some collectors are equipped with a barrier to reduce convection losses. This takes the form of a film of plastic, such as Teflon, between the absorber and the glass pane. In some countries collectors are offered with translucent heat insulation under the glass panel.

HOUSING AND GLASS PANEL

The absorber and thermal insulation are installed in a box and are enclosed on the top with a light-transmitting material for protection and to achieve the so-called greenhouse effect.

Glass or occasionally plastic is used for the cover. Low-ferrous glass (which is highly transparent) is mainly used, in the form of safety glass, 3–4 mm thick. The light-transmitting coefficient is maximally 91%.

Requirements for the transparent cover are as follows (see also Table 2.3):

- high light transmittance during the whole service life of the collector
- low reflection
- protection from the cooling effects of the wind and convection
- protection from moisture
- stability with regard to mechanical loads (hailstones, broken branches etc.).

The first products are now coming onto the international market with special coatings on the glazing to reduce reflections and thus increase the efficiency.

SEALS

Seals prevent the ingress of water, dust and insects. The seals between the glass panel and the housing consist of EPDM (ethylene propylene diene monomer) material or silicon rubber. The rear wall is sealed to the frame with silicon. For tube entry, seals made of silicon or fluorinated rubber are suitable (maximum application temperature 200°C).

Table 2.3. Characteristics of different cover and box materials

Cover	Glass	Plastic
Transmission values	Long-term stability	Deterioration due to embrittlement, tarnishing, scratches
Mechanical stability	Stable	Stable
Cost	Higher	Lower
Weight	Higher	Lower

Housing	Aluminium	Steel plate	Plastic	Wood, bonded waterproof
Weight	Low	High	Medium	High
Processing	Easy	Easy	Medium	Difficult
Energy requirement	High	Low	Medium	Low
Cost	High	Low	Low	Medium
Other	Increase in energy recovery time, recyclable	Hardly ever used	Seldom used	Ecological material only for in-roof mounting

2.2.2.2 WORKING PRINCIPLE OF A GLAZED FLAT-PLATE COLLECTOR

See Figure 2.10.

The irradiance (G_0) hits the glass cover. Here, even before it enters the collector, a small part of the energy (G_1) is reflected at the outer and inner surfaces of the pane. The selectively coated surface of the absorber also reflects a small part of the light (G_2) and converts the remaining radiation into heat. With good thermal insulation on the rear and on the sides of the collector using standard, non-combustible insulating materials such as mineral wool and/or CFC (chlorofluorocarbon)-free polyurethane foam sheets, the energy losses through thermal conduction (Q_1) are reduced as much as possible.

The transparent cover on the front of the collector has the task of reducing losses from the absorber surface through thermal radiation and convection (Q_2). By this means only convection and radiation losses from the internally heated glass pane to the surroundings occur.

From the irradiated solar energy (G_0), because of the various energy losses G_1, G_2, Q_1 and Q_2, the remaining heat (Q_3) is finally usable.

COLLECTOR EFFICIENCY COEFFICIENT

The *efficiency*, η, of a collector is defined as the ratio of usable thermal power to the irradiated solar energy flux:

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

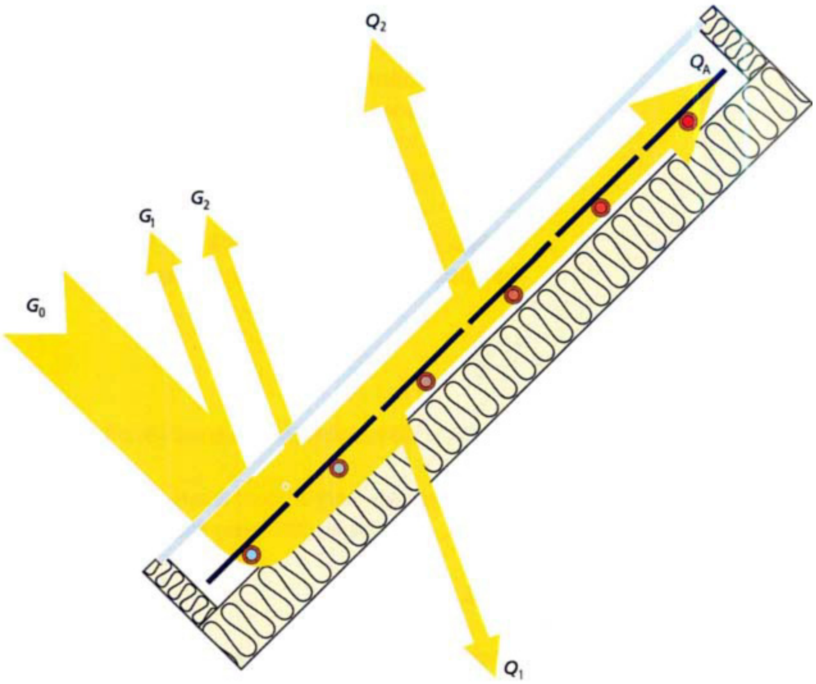


Figure 2.10.
Energy flows in the collector

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

The efficiency is influenced by the design of the collector: more specifically, it is influenced by the particular optical (G_1 and G_2) and thermal ($\dot{Q}_1$ and $\dot{Q}_2$) losses (see Figure 2.11).

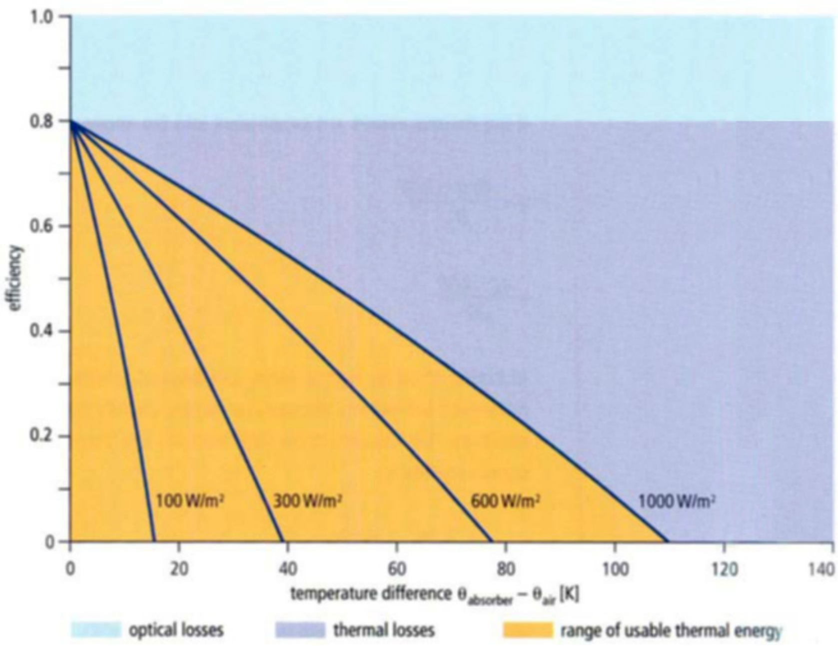


Figure 2.11.
Optical and thermal losses

The optical losses describe the proportion of the solar irradiance that cannot be absorbed by the absorber. They are dependent on the transparency of the glass cover (degree of transmission, τ) and the absorption capacity of the absorber surface (degree of absorption, α) and are described by the *optical efficiency*:

$$\eta_0 = \tau\alpha$$

The thermal losses are dependent on the temperature difference between the absorber and the outside air, on the insolation, and on the construction of the collector. The influence of the construction is described by the *heat loss coefficient*, *k* (or *k*-value), which is measured in W/m²K.

As the temperature difference between the absorber and the outside air increases, the heat losses increase for a constant irradiance, so that the efficiency reduces. It is therefore important for the yield of a thermal solar system to ensure a low return temperature and a high irradiance.

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 Q_A is the available thermal power (W/m²), and G is the irradiance incident on the glass pane (W/m²).

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/m²), and $\dot{Q}_L$ represents the thermal losses (W/m²).

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/m²K):

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

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

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

$$= \frac{\eta_0 - k\Delta\theta}{G}$$

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/m²K), and k_2 is the quadratic heat loss coefficient (W/m²K²).

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.

NUMERICAL VALUES
The characteristic numbers given are the criteria for comparing the qualities of different collectors. Good glazed flat-plate collectors with spectral-selective absorbers have an optical efficiency, η_0, greater than 0.8 and a k-value of less than 3.5 W/m²K.

The average annual efficiency of a complete system with glazed flat-plate collectors is 35–40%. With an annual amount of solar radiation of 1000 kWh/m² (as in central Europe) this corresponds to an energy yield of 350–400 kWh/m²a. In sunnier climates, the radiation may increase to over 2200 kWh/m² and the corresponding energy yield of the system may then surpass 770–880 kWh/m²a. These yields assume a sensibly dimensioned system and corresponding consumption.

ADVANTAGES AND DISADVANTAGES OF A GLAZED FLAT-PLATE COLLECTOR
Advantages:

- It is cheaper than a vacuum collector (see section 2.2.3).
- It offers multiple mounting options (on-roof, integrated into the roof, façade mounting and free installation).
- It has a good price/performance ratio.
- It has good possibilities for do-it-yourself assembly (collector construction kits).

Disadvantages:

- It has a lower efficiency than vacuum collectors, because its k-value is higher.
- A supporting system is necessary for flat roof mounting (with anchoring or counterweights).
- It is not suitable for generating higher temperatures, as required for, say, steam generation, or for heat supplies to absorption-type refrigerating machines.
- It requires more roof space than vacuum collectors do.

2.2.2.3 SPECIAL DESIGNS

HYBRID COLLECTOR
A hybrid collector is a combination of a thermal glazed flat-plate collector with solar cells that convert the sunlight into electrical energy. The heat created is used, for instance, to heat domestic water. The solar cells are electrically isolated on the surface of a liquid-cooled absorber with which they are thermally conductively connected. The electrical yields are in the same range as those of conventional photovoltaic systems, and the thermal yields are in the range of collectors without selectively coated absorbers. These collectors are still being developed. Whether this will be a product that succeeds on the market, or whether thermal collectors and photovoltaic modules will in future be offered separately but possibly in a uniform grid dimension and roofing system, remains to be seen.

ICS (INTEGRAL COLLECTOR AND STORAGE) SYSTEM
Here the collector and water store form one structural unit. The following components are not required: heat exchanger, piping for the solar circuit, controller and recirculation pump. The ICS presents an interesting alternative to the standard glazed flat-plate collector from the points of view of efficiency and price/performance ratio. However, simple collectors, with only a glass pane covering them, are not frost-proof, and must therefore be emptied in winter in climates where freezing can occur. Some products use *translucent insulation material* (TIM) behind the glass pane to reduce heat losses, but there is still a risk of freezing of the supply and return lines. ICS systems are widely used in southern Europe.

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 2.12). 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

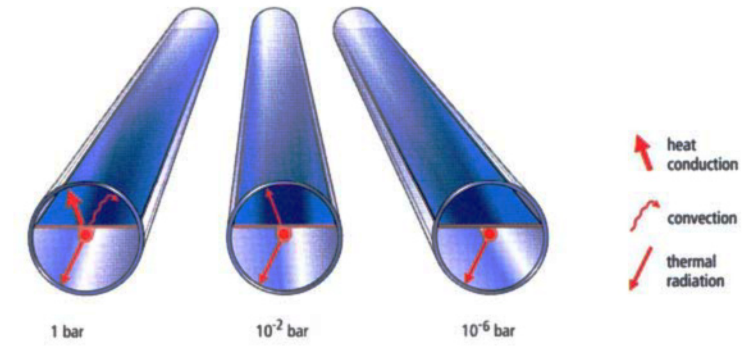


Figure 2.12.
The principle of vacuum thermal insulation

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 ϵ value). The heat losses to the surrounding air are therefore significantly reduced. Even with an absorber temperature of 120°C or more the glass tube remains cold on the outside. Most vacuum tubes are evacuated down to 10^{-5} bar.

ABSORBER, GLASS TUBE, COLLECTOR AND DISTRIBUTOR BOXES

For evacuated tube collectors, the absorber is installed as either flat or upward-vaulted metal strips or as a coating applied to an internal glass bulb in an evacuated glass tube. The forces arising from the vacuum in the tube are very easily taken up by the high compression strength of the tubular form.

An evacuated tube collector consists of a number of tubes that are connected together and which are linked at the top by an insulated distributor or collector box, in which the feed or return lines run. At the base the tubes are fitted to a rail with tube holders. There are two main sorts of evacuated tube collector: the direct flow-through type and the heat-pipe type.

DIRECT FLOW-THROUGH EVACUATED TUBE COLLECTORS

In this design (Figure 2.13) 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.

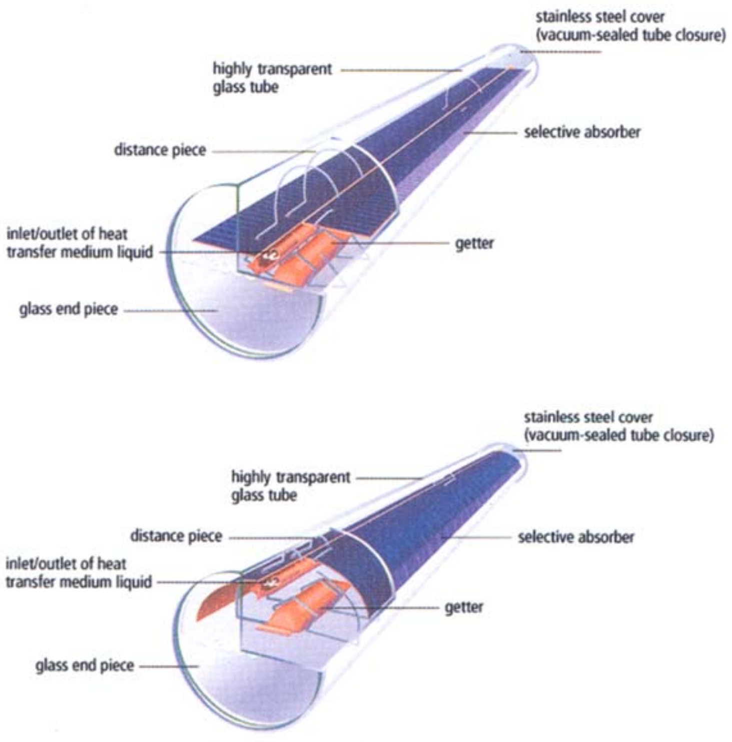
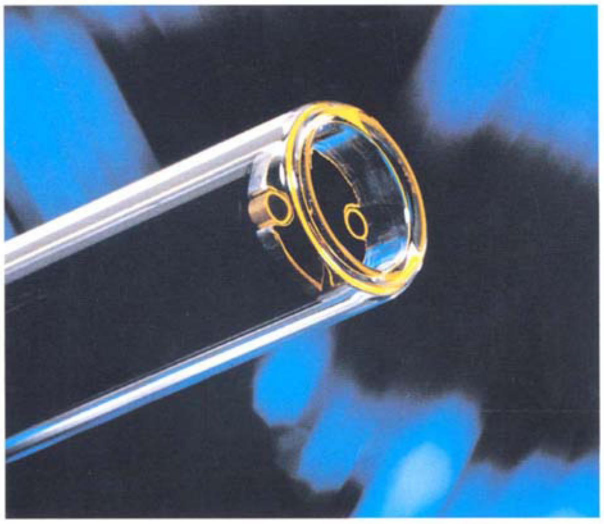


Figure 2.13.
Cross-sectional view of a direct flow-through evacuated tube collector (Lux 2000 and 2000R, ThermoLUX, Kempten)

Next Page

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

A particular design of direct flow-through evacuated tube collector marketed in some countries is the *Sydney collector* (Figure 2.14). The collector tube consists of a vacuum-sealed double tube. The inner glass bulb is provided with a selective coating of a metal carbon compound on a copper base. Into this evacuated double tube is plugged a thermal conducting plate in connection with a U-tube to which the heat is transferred. Several tubes are combined into one module (between 6 and 21, according to supplier). To increase the radiation gain the collector is fitted with external reflectors in the sloping roof version. The flat roof version requires a light background such as gravel or reflective foil, as it does not have reflectors.



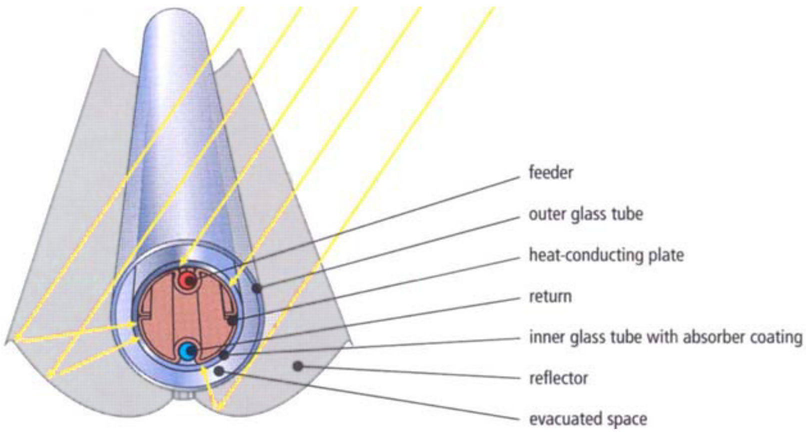


Figure 2.14. Sydney tube (microtherm, Lods)

HEAT-PIPE EVACUATED TUBE COLLECTORS

In this type of collector a selectively coated absorber strip, which is metallically bonded to a heat pipe, is plugged into the evacuated glass tube. The heat pipe is filled with alcohol or water in a vacuum, which evaporates at temperatures as low as 25°C. The vapour thus occurring rises upwards. At the upper end of the heat pipe the heat released by condensation of the vapour is transferred via a heat exchanger (condenser) to the heat transfer medium as it flows by. The condensate flows back down into the heat pipe to take up the heat again. For appropriate functioning of the tubes they must be installed at a minimum slope of 25°.

Heat pipe evacuated tube collectors are offered in two versions, one with a dry and one with a wet connection. For the dry type (Figure 2.15), the condenser completely surrounds the collector, and provides a good heat-conducting link to a double tube heat exchanger: The heat transfer takes place from the condenser via the tube wall to the heat transfer medium. This permits defective tubes to be exchanged without emptying the solar circuit.

3 Systems for single-family houses

3.1 Introduction

There are several main types of solar water heater for single-family houses:

- *Thermosyphon and forced circulation systems*. Thermosyphon systems do not require pumps, as in this case gravity is used for liquid transport, whereas systems with forced circulation require circulating pumps for this purpose.
- *Open and closed systems*. Open systems have an open container at the highest point of the solar circuit, which absorbs the volumetric expansion of the liquid caused by the temperature changes. The pressure in open systems thereby corresponds at its maximum to the static pressure of the liquid column. Closed (sealed) systems operate with a higher pressure (1.5–10 bar), which influences the physical properties (such as the evaporation temperature) of the solar liquid. Special safety devices are necessary for closed systems.
- *Single-circuit (direct) and twin-circuit (indirect) systems*. In the first case the domestic water circulates from the storage vessel to the collector and back again. In the second case the system is separated into one solar circuit and one domestic water circuit. The solar circuit includes the collectors, the ascending pipes, the solar pump with safety equipment and a heat exchanger. A mixture of water and antifreeze agent can be used as the heat transfer fluid. The domestic water circuit includes the storage vessel as well as the cold water and hot water installations of the house.
- *Filled and drainback systems*. Indirect systems can have a collector circuit that is either completely filled or only partly filled. In the latter systems, which are called drainback systems, the collector drains completely when the collector pump is switched off.

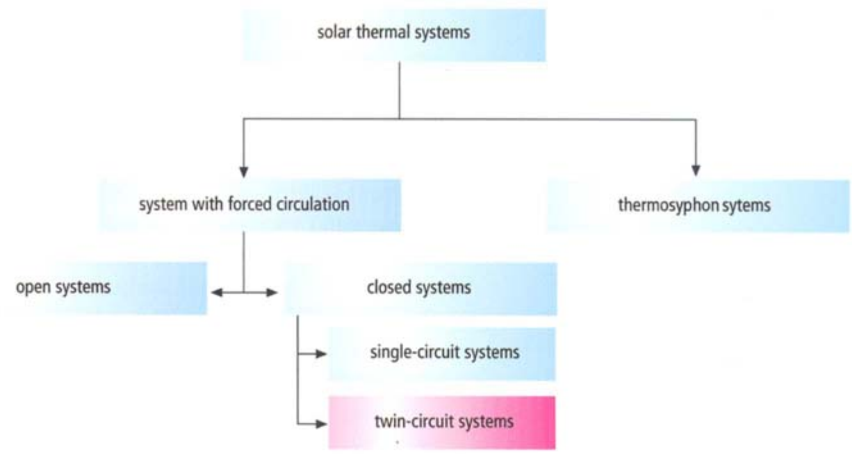


Figure 3.1. Classification of solar thermal systems

Systems with forced circulation are predominant in temperate climates, such as in central and northern Europe. In southern Europe, Australia, Israel and other – mostly sunny – countries, thermosyphon systems are the most common type.

In order to provide an overview of the multiplicity of possible circuits, we shall divide them into the following functional sectors:

- solar energy feed: charging of the store with solar energy
- auxiliary heating: charging of the store by conventional heating
- heat removal: removal of the stored heat through hot water consumption or other means.

Then we shall list the essential variants of each and consider the most important systems, which can be combined from these. *Note that, for clarity, the schematic diagrams in this chapter do not show safety valves or vents.*

3.2 Systems for charging/discharging the store

3.2.1 Charging by means of solar energy

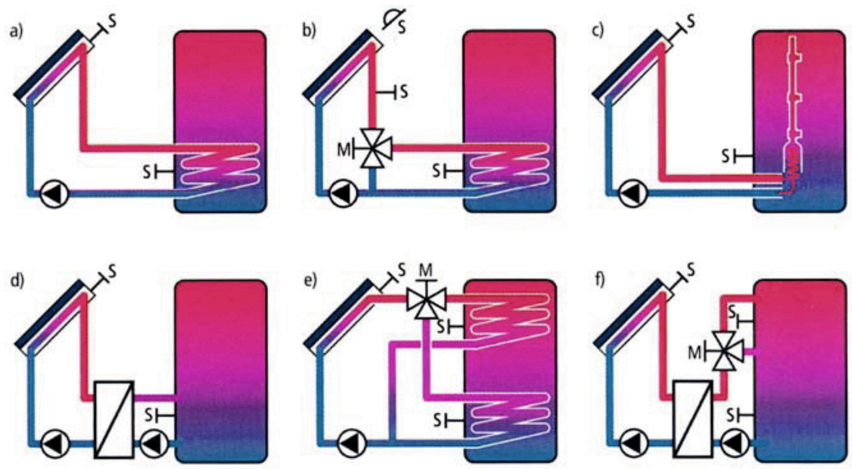


Figure 3.2.
Types of store charging with solar energy (S = sensor)

(a) *Internal solar heat exchanger*. The heat exchanger is normally designed as a finned or plain tube coil, which is arranged in the lower area of the store. Thermal transmission to the domestic water takes place through thermal conduction, and as a result of this convection takes place: that is, the heated water rises as a result of its lower density.

(b) *Internal solar heat exchanger with bypass circuit*. This is a variant of system (a) for larger systems. A radiation sensor measures the solar radiation. At a threshold value of, for example, 200 W/m^2 the controller switches on the solar pump, and the three-way valve initially bypasses the heat exchanger. The solar circuit heats up. When the set temperature difference with the store has been reached at the flow sensor, the controller switches over the valve and the store is charged with heat.

(c) *Stratum charging with self-regulating stratified charger*. The central core of this store-charging method is a riser pipe with two or more admission ports at different heights and a heat exchanger installed below. The heat exchanger heats up the water surrounding it in the riser pipe, and the water rises up. This causes a pronounced temperature-stratification effect, and in the upper area a useful temperature is very soon achieved.

(d) *External heat exchanger*. The solar liquid flows through the primary side of an external plate heat exchanger. For charging the store a second circulating pump draws cold water from the bottom of the store. This flows through the secondary side of the heat exchanger in a counter-flow and then flows back into the middle of the store. An external heat exchanger has better thermal transfer properties than an internal type. Stores without internal fittings can also be used. The bypass circuit (b) can be implemented without the three-way valve by controlling the two pumps separately. For this purpose sensor arrangement (b) should be selected.

(e) *Stratified charging system* with two internal heat exchangers and feed via a three-way valve at two different heights.

(f) As (e) but with an *external heat exchanger*.

The advantage of stratified charging systems (rapid reaching of useful temperatures in the standby area) is greatest in connection with the *low-flow* concept. In low-flow systems, sometimes also called *matched-flow* or *single-pass* systems, only about 25 l of heat transfer fluid circulates per square metre of collector area. The effect of this is that the efficiency of the collectors is increased slightly, and that higher temperature differences occur between the collector and water tank. This can increase the system efficiency, because less pump energy is needed, and after only a few hours a layer of hot water may accumulate at the top of the tank. If hot water is needed at that moment, it can be supplied entirely or almost entirely from the solar heat, and auxiliary energy is saved. Most solar water heaters can be used as low-flow systems, but there are also specially designed systems with optimized water tanks and heat exchangers. The advantage of low-flow systems is that thinner, and hence cheaper, standpipes can be used. These also lose less heat and, together with the minimal amount of heat transfer fluid and a smaller pump, help to reduce the total cost of the solar heating system.

3.2.2 Charging by means of auxiliary heating

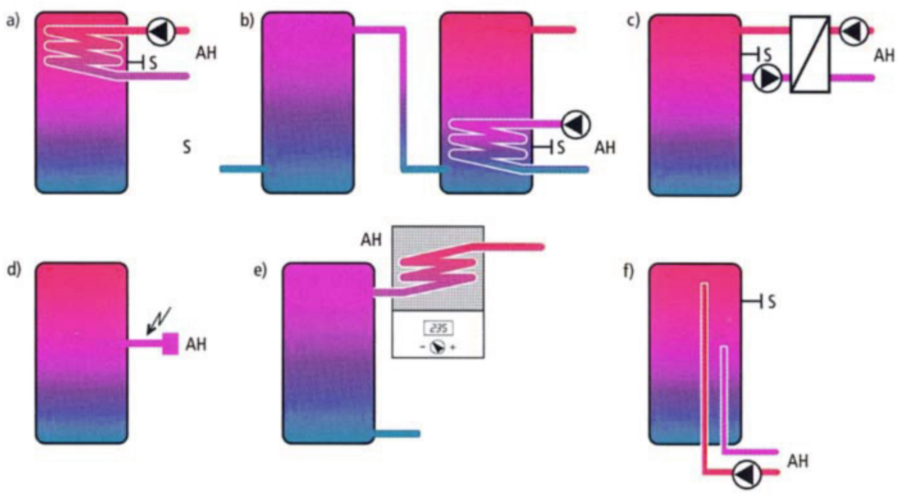


Figure 3.3.
Types of store charging with auxiliary heating

(a) *Domestic water store.* The standby volume is heated as necessary via the upper heat exchanger, using an oil or gas boiler with store priority switching. Recently, in several countries, wood has started to be used again (for example in the form of pellets) as a growing fuel resource for heating purposes that is CO_2-neutral. In the case of the cascade connection of two stores the additional heat exchanger can be located in the top or bottom of the second store according to the size of the required standby volume.
(b) *Domestic water store.* Auxiliary heating of the standby volume by an external heat exchanger.
(c) *Domestic water store.* Electrical auxiliary heating of the standby area. Electrical power is acceptable for use as heating only in exceptional cases, as electricity generation involves high losses. (Electricity is generated in a conventional power station with an efficiency of about 30–50%, and on top of this loss are the line losses to the consumer.)
(d) *Domestic water store.* Top-up heating by a downstream instantaneous heater (gas or electricity). The device must be thermally controlled and designed to accept preheated water: that is, it only heats up as much as is required to achieve a set exit temperature. Advantage: the whole store is available for solar energy, and there are lower store losses compared with top-up heating inside the store. Disadvantage: in the case of electricity, similar to (c). In the case of gas or oil, there are very few compatible appliances.
(e) *Buffer (thermal) store.* Top-up heating via admission pipe. The store-charging pump draws the water to be heated from the middle of the store. This is heated by the boiler and fed into the top of the store via an admission pipe.
(f) *Buffer (thermal) store.* Direct top-up heating of a separate buffer store. Warm heating water is withdrawn from the middle of the store and hot water is fed in again at the top, as in (e), but in this case the pipes are installed at a corresponding height at the side.

3.2.3 Store discharge

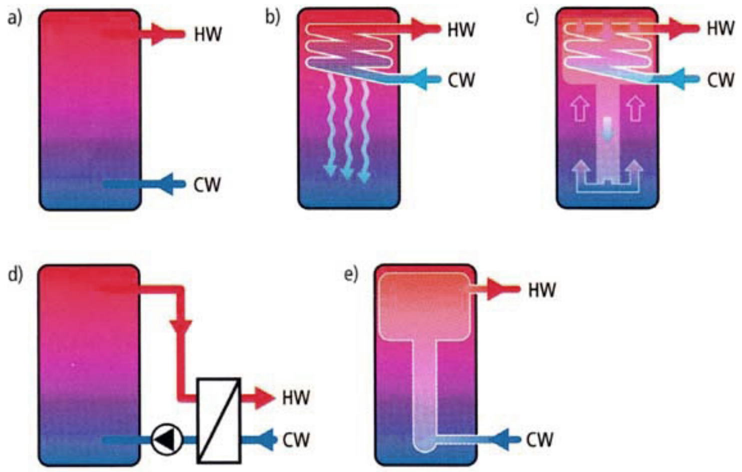


Figure 3.4.
Methods of store discharge

(a) *Domestic water store.* The water is withdrawn from the top in the hottest part of the store (standby area). Cold water flows in at the bottom in a corresponding amount. Almost the whole amount of stored hot water can be withdrawn.
(b) *Buffer store.* Discharge takes place in the upper area via an internal heat exchanger. The disadvantage is that the upper storage area is significantly cooled down by the cold water (8–12°C) flowing into the heat exchanger. This causes a significant amount of circulation, which causes mixing of the waters: that is, the store temperature layers are destroyed.
(c) *Improvement on (b).* The cooled store water descends within a downpipe and pushes the warmer water uniformly upwards. In this way the hottest water is always available at the top, and the stratification is hardly disturbed.
(d) *Buffer store.* Discharging is through an external heat exchanger.
(e) *Combined store.* Cold water enters the domestic water store right at the bottom. It heats up according to the layers in the buffer store and is removed from the hot area at the top.

Two groups of systems can be combined from the modules described above:

- systems for domestic water heating
- systems for domestic water heating and heating support.

These are described in the next two sections.

3.3 Systems for heating domestic water

The standard system (Figure 3.5) has been widely accepted for use in small 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

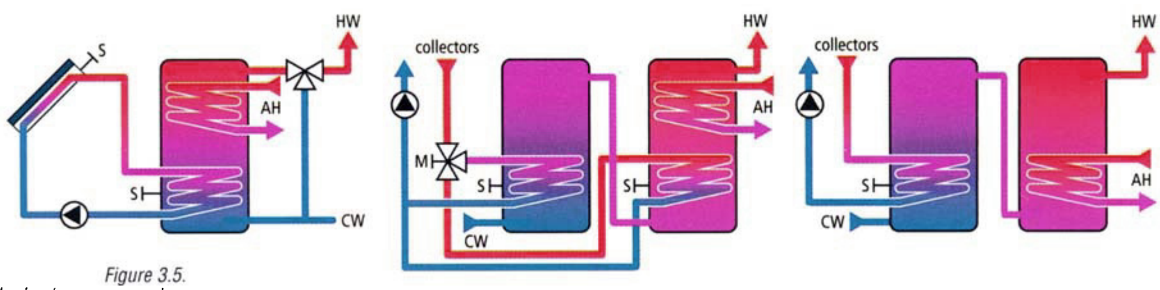


Figure 3.5.
Standard solar energy system

maximum draw-off temperature by means of a thermostatic three-way blending valve (see Chapter 2, section 2.3.6).

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 in the lower store area. When the temperature on the boiler controller for the standby volume falls below a set temperature, 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). In the case of the cascade connection of two stores, either both stores can be heated by solar energy where the draw-off store is charged as a priority, or only the preheating store is charged by solar energy and the draw-off store is top-up heated as necessary.

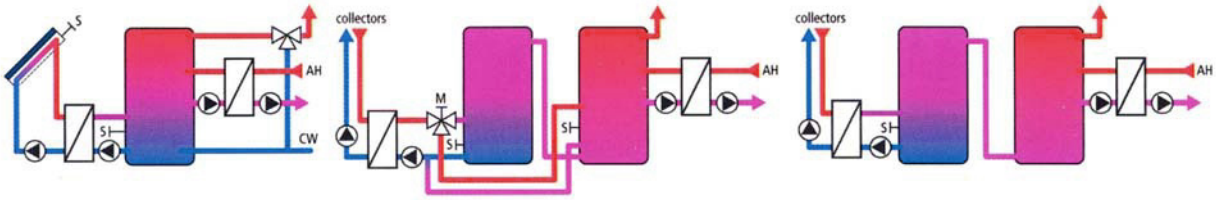
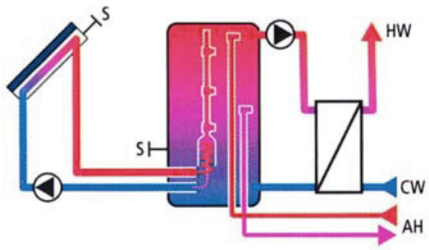


Figure 3.6.
The same system configuration as Figure 3.5 but with external heat exchangers

Through the use of a special *stratified store* either as a domestic hot water store or as a buffer store (Figure 3.7), which is used only for domestic water heating for hygiene reasons, the heat from the solar collector is specifically fed into the matching temperature layer in the store. The significantly reduced mixing process leads to a usable temperature level much faster than for all the other systems described here, and the frequency of auxiliary heating is reduced. When the stratified store operates with buffer water, the heat for the domestic water is discharged by means of an external once-through heat exchanger. Also important for the performance of this system is good matching of the discharge control system to the different tapping rates.

Figure 3.8 shows a *buffer store* with external charging and an internal output heat exchanger, which includes an internal downpipe and direct auxiliary heating by the boiler (for hygiene reasons it is exclusively used here for domestic water heating).



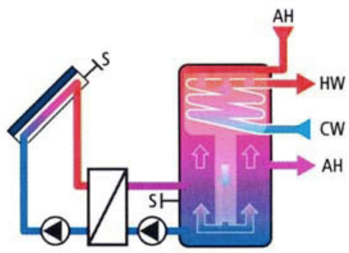


Figure 3.7 (left).
Stratified store as buffer storage

Figure 3.8 (right).
Buffer store with external charging and internal output heat exchanger

In a *twin-store system* (see Figure 3.9) the solar circuit charges a buffer store via an internal or external heat exchanger, from which in turn a downstream domestic water store is supplied with heat. This then receives auxiliary heating in the upper area. This variant has proved to be more favourable than auxiliary heating in the buffer store. [15] The temperature in the buffer store is thus determined entirely by the solar radiation.

Lower energy losses occur compared with auxiliary heating of the buffer store. In larger systems the store volume is divided into buffer and domestic water areas for water hygiene reasons (Legionella problems) and for energy saving.

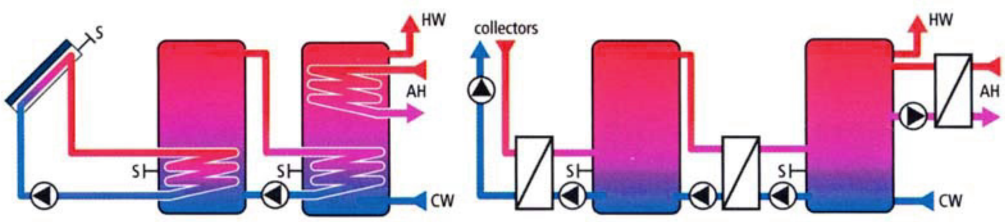


Figure 3.9.
Twin-store systems

Figure 3.10 shows a *combined store system*: for hygienic reasons, this is used here exclusively for domestic water heating. In comparison with standard systems, this store contains a smaller domestic water volume. Hence the water dwell time in the store is shorter. The surrounding buffer (thermal storage) water is used only as intermediate storage for the heat.

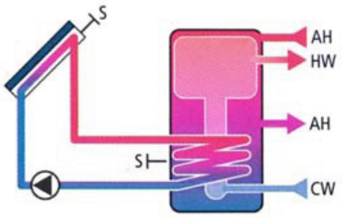


Figure 3.10.
Combined store system

3.4 Systems for heating domestic water and space heating

If a solar energy system is considered in the planning stage of the whole heating system, and the house has a central space heating installation, it is possible to use solar heating to augment the space heating. The reduced heat requirements of low-energy houses and the higher performance of modern solar energy systems encourage the trend to install solar systems with space heating support in countries with cold or temperate climates. In spite of the comparatively low solar fraction proportion for room heating (typically 10–20%), combined systems for domestic water heating and space heating support have a higher primary energy substitution than pure domestic water systems.

The space heating support is implemented in such a way that either the boiler operates on the store and this then operates on the space heating circuit, or the temperature of the heating return flow is raised by means of the solar system. The heating boiler then only has to supply little or no heat.

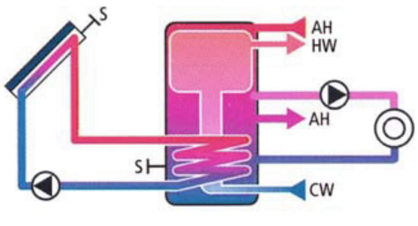
By means of a larger collector surface area, these systems are over-dimensioned in the seasons in which space heating is not necessary. For the removal of excessive heat see Chapter 2, section 2.5.4.

3.4.1 Combined store system (store-in-store system)

See Figure 3.11. A small domestic water store is permanently fitted in the buffer store. The solar circuit is led via an internal heat exchanger, and the auxiliary heating is charged directly into the upper area. The heating circuit draws heating water from halfway up the store and feeds the cooled heating circuit return flow back into the bottom of the buffer store. The cold water that flows back into the domestic water store does, however, impair the heat layers in the event of high draw-off rates. The system requires no expensive control technology. It is mostly found in central Europe, particularly in Switzerland.

3.4.2 System with buffer store, internal heat exchanger for heat removal and downpipe

See Figure 3.12. The store can be charged by the solar circuit via an external heat exchanger at two levels. The corresponding level is selected according to the temperature. Domestic hot water is removed via a special internal heat exchanger, which is fitted above a downpipe. If the heat exchanger cools down because of the inflow of cold water, a downward flow is set up within the pipe and then upwards within the store. In this way the heat exchanger always has sufficient flow rate. The



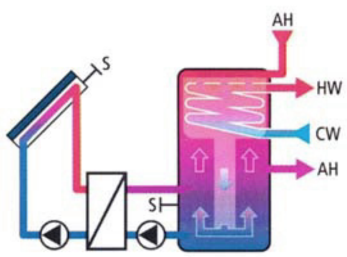


Figure 3.11 (left).
Combined store system for domestic water heating and space heating

Figure 3.12 (right).
Buffer store system

auxiliary heating heats up the upper area of the store. The heating return line is led either to the solar return level via the store or, if the store is too cold, directly to the heating boiler, bypassing the store. The system does not require an expensive control system, but temperature stratification is not optimally achieved.

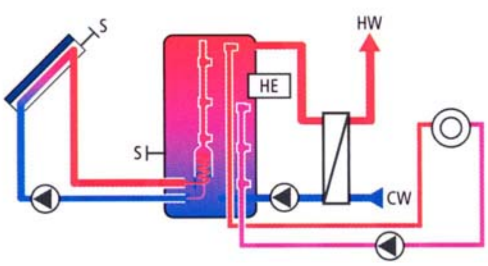
3.4.3 Stratified store with hot water heating in once-through flow and heating support

Stratified stores, which can be used for heating domestic water only, are also designed for space heating support. The two-layer chargers shown in Figure 3.13 ensure that the solar heat and the heating return pipes, at different temperatures, are brought in at the matching temperature layers of the store. The auxiliary heating takes place in the upper area of the store. Removal of the heat for domestic water heating takes place via an external heat exchanger with a speed-controlled pump. The system operates very efficiently, but special attention must be paid to the control of the discharge pump. For prefabricated systems, however, this does not pose any practical restrictions.

3.4.4 Twin store system

See Figure 3.14. Here we have the classical separation between domestic water and heating buffer stores. The solar circuit charges both stores in the lower area, but the domestic water store has the priority. The auxiliary heating charges both stores in the upper area. Each store supplies the system that follows it. This type of system with additional equipment can be used for solar heating support, making use of the existing solar store.

Disadvantages, however, in comparison with the previously mentioned systems are a larger physical space requirement, higher pipework costs and higher store losses.



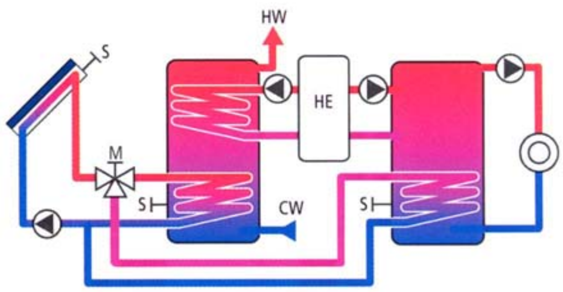


Figure 3.13 (left). Stratified store system

Figure 3.14 (right). Twin-store system

3.5 Planning and dimensioning

Right at the start of system planning it is important to record accurately the conditions at the site. This includes clarifying all the details that are important for planning and installation, and obtaining data about the building, the hot water consumption and, if necessary, the heat requirement for the house. It is also necessary to sketch all the important details that are required for preparing the quotation.

3.5.1 Important features for preparing the quotation

- Is the collector shaded by trees, parts of the building or other buildings (present/future depending on the time of year; see section 1.1.4)?
- Is the collector temperature sensor shaded?
- What is the most favourable alignment of the collector surface (see Figure 1.15)?
- What is the future accessibility of the collector for maintenance? Access to any chimney must always be guaranteed.
- Do not install collectors beneath aerials and similar equipment, because of bird droppings.
- What is the shortest possible path to the store (< 20 m)?
- Are there any requirements with respect to listed buildings?
- Use and complete checklists (see below).

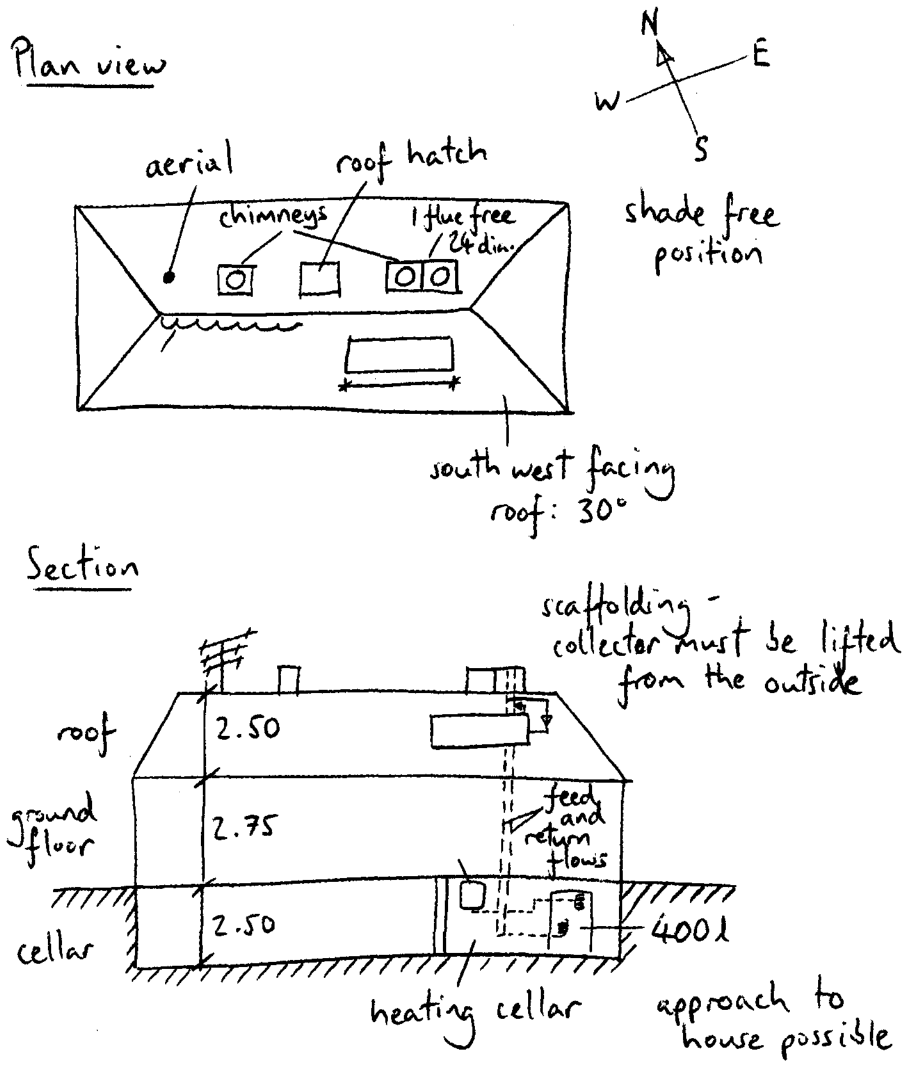


Figure 3.15.
Preparation of an initial system sketch[16]

- Is extra equipment required (such as an inclined hoist, or a crane)?
- Are any safety measures necessary (for example safety equipment, safety belts)?
- What type of collector installation is possible/desirable (on-roof, in-roof)?
- Who will install the collector fixing brackets (roofer)?
- Are roof tiles laid in a mortar bed (increased cost of installation)?
- Can the roof be walked on (fragile tiles)?
- Flat roof: bearing load of roof skin (fragile roof)?
- Note minimum distance from mortared ridge tiles.
- What is the best way to fit the piping with good insulation and make the roof penetrations?
- Does central hot water heating already exist?
- How will the solar store be transported to reach its installed location? For example, a 400 l store weighs 145 kg, is 1.7 m high and 0.62 m diameter.
- How does the auxiliary heating of the store take place (integration into the existing heating system)?
- How, and by whom, is the electrical work to be done (mains connection, lightning protection/earthing, control system)?
- Is a waste water connection available in the store installation room?
- If a solar energy system cannot be considered at present for cost reasons, at least the installation of collector pipes and sensor cables and possibly even the installation of a solar store should take place for later retrofitting.

DATA FOR A THERMAL SOLAR ENERGY SYSTEM

Name:
Road:
Telephone:
Property address:
Customer special requirements:

House type: ○ One/two-family home ○ Multiple-family home
No. of living units: Year of construction:

Use of sun's energy for: ○ Hot water (DHW) ○ Heating swimming pool

No. of people:
Estimated/measured hot water consumption (litres per person/day)
○ Low (30 l) ○ Average (50 l) ○ High (80 l)
Other hot water requirements: ○ Washing machine ○ Dishwasher

Type of installation: ○ In-roof ○ On-roof ○ Free-standing
○ Flat roof ○ Façade/wall/balustrade
Roof covering: Description, type: Colour:
○ Tiles
○ Stone tiles
○ Slates
○ Other
Pitch Alignment
Height from ground to eaves:
Usable installation area Height: Width:
Shade:

Height of solar store installation space (m):
Minimum door width (m):
Single length of connecting pipe from store to collector (m):
Work required for connection pipe from store to collector:
Work required for connection pipe from store to hot water distribution:

If store already exists: Type:
Make:
Volume: (l)
Heating boiler: Type:
Make:
Power (kW):
Circulation line: ○ Yes ○ No
Thermal insulation: ○ Good ○ Poor
Running time of circulation pump: ○ Continuous ○ From To

Only for swimming pool water heating

Pool surface area (m^2):

Covered: ○ Yes ○ No

Required water temperature (°C):

Swimming season From: To:

Only for heating support

The living floor area to be heated (m^2):

The space heating feed and return flow temperature (°C):

Fuel:

Fuel consumption (l/year, m^3/year):

Notes:

Place:

Date:

Filled in by:

3.5.2 The dimensioning of systems for domestic water heating

3.5.2.1 DESIGN OBJECTIVES

In temperate climates, a common design objective is that a solar water heater for one-family homes should cover about 90% of the hot water demand during the summer months by means of solar energy. This will have the effect that the heating boiler can remain dormant during most of this period (where drinking water regulations allow this). In this way not only is the environment protected, but also money is saved and the life of the heating boiler is extended.

In the remaining months, when the heating boiler has to operate anyway, the auxiliary heating system supplies the necessary heat not otherwise provided by the sun.

In sunny climates, the common design goal is either to supply the hot water consumption fully from solar energy, or to supply full coverage for most of the year and use a back-up heater (often an electrical element immersed in the solar tank) for only a few weeks or months per year.

3.5.2.2 SOLAR FRACTION

The solar fraction is described as the ratio of solar heat yield to the total energy requirement for hot water heating:

$$SF = \frac{Q_S}{Q_S + Q_{aux}} \times 100$$

where SF is the solar fraction (%), Q_S is the solar heat yield (kWh), and Q_{aux} is the auxiliary heating requirement (kWh). The higher the solar fraction in a solar energy system, the lower the amount of fossil energy required for auxiliary heating: in the extreme case (SF = 100%) none at all.

Figure 3.16a shows the monthly solar fractions for a solar thermal system in a temperate climate. It can be seen that in the case of 100% solar fraction during the radiation-rich months from May to August, an annual fraction of 60% is achieved.

When a system is properly designed, for instance to cover almost the complete demand in the summer months in central Europe, the addition of extra collector area would not lead to correspondingly higher output. In periods with high irradiation, the system would produce excess heat, which would lead not only to frequent high

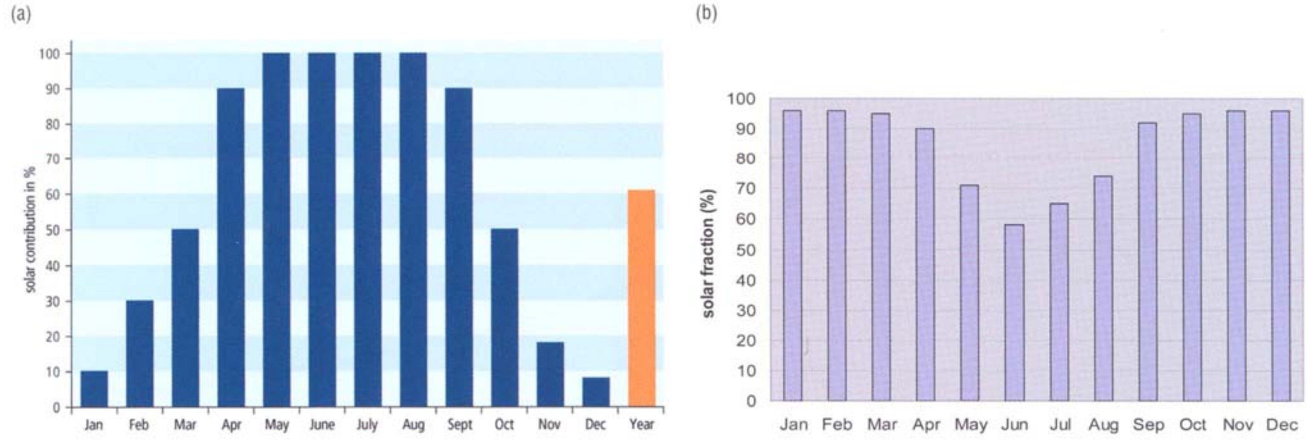


Figure 3.16.
Solar fraction for each month for: (a) a system in Northern Europe (55°N), designed to cover the hot water demand fully in the summer months; (b) a system in Sydney, designed to cover 85% of the hot water demand over the year

thermal loads on the collectors (stagnation), but also to a lower efficiency (additional costs are higher than additional yield). In periods with lower irradiation, the output would be higher but the total annual output per square metre of collector would be lower than with the original system.

In systems with an auxiliary heat exchanger inside the same tank as the solar-heated water, the tank heat losses result from both the solar heat and the auxiliary heat brought into the tank. Depending on how the heat losses from the tank are attributed to the solar heat and/or the auxiliary heat, the solar fraction may then be defined in different ways.

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:

$$SE = \frac{\dot{Q}_S}{E_G A} \times 100$$

where SE is the system efficiency (%), $\dot{Q}_S$ 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:

$A = 6\ \text{m}^2$
$E_G = 1000\ \text{kWh/m}^2\text{a}$ (central Europe)
$\dot{Q}_s = 2100\ \text{kWh/a}$

Then the system efficiency is given by

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

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.

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

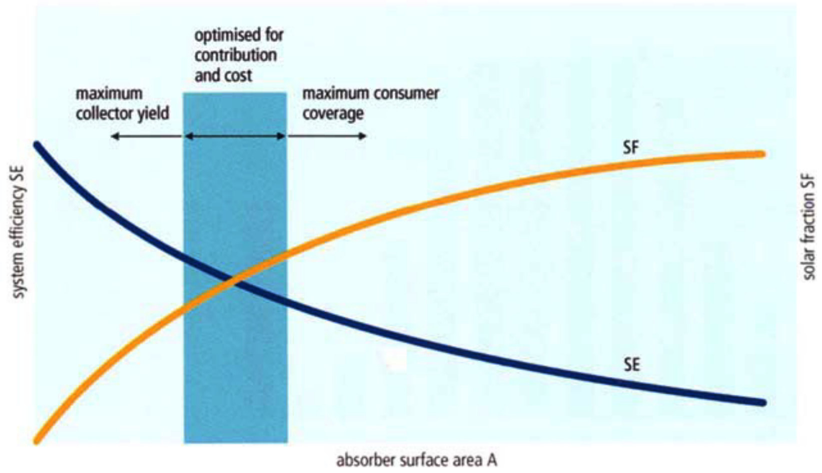


Figure 3.17.
Solar fraction and system efficiency[17]

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)	3 l
1 × showering (40°C)	35 l
1 × bathing (40°C)	120 l
1 × hair washing	9 l
Cleaning	3 l per person per day
Cooking	2 l per person per day
1 × dishwashing (50°C)	20 l
1 × washing machine (50°C)	30 l

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):

- low consumption 20–30 l
- average consumption 30–50 l
- high consumption 50–70 l.

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 per person per day (45°C), 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 2.3.7 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_{HW} = 4 persons × 50 l (45°C) + 16 l (45°C) = 216 l (45°C) per day

*2 × 20 l (50°C) + 2 × 30 l (50°C)</7 days ≈ 16 l (45°C) for dishwashing and the washing machine.

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:

$$Q_{HW} = V_{HW} c_W \Delta\theta$$

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:

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

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. 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 equivalent to the above-mentioned 216 l at 45°C, using a cold water temperature of 10°C, is calculated as follows:

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

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:

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

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

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

Next Page

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 m² of glazed flat-plate collectors of 15% ($\dot{Q}_S$ = 5 m² × 1000 kWh/m²a × 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:

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

Therefore the resulting heat losses Q_G are

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

This corresponds to an annual heat gain for 1 m² 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 θ_A = 20°C:

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

The pipe diameter must be inserted here in m.

Example:

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

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

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.

4 Installation, commissioning, maintenance and servicing

The installation of thermal solar energy systems involves three trade skills:

- roofing
- heat engineering (that is, plumbing and heating appliances)
- electrical.

In other words, specialist knowledge of all three areas is required if an installation is to be successful. The technical documentation of the manufacturer or the specialist literature for an individual component (particularly the installation instructions) are often insufficient.

The area in which the plumber, or the heating fitter, is often in totally new territory is usually the roofing skills. Whenever a collector assembly (field) is installed on a roof and the connecting pipes are laid into the house, work on the roof structure is also involved. It is therefore important to know and to follow the respective standards and regulations. This should help to clarify the question of which tasks the installer of solar systems can carry out, and which require a specialist roofer. For example, intervention by the heating fitter into flat roofs with plastic sheeting is definitely *not* recommended.

As it is not possible to give details of the standards and regulations for all countries in the world, this chapter gives general aspects and details of some common constructions and situations. For more information on a specific country, the reader is encouraged to make use of the references given in section 4.5.

Work tasks that the installer is likely to be familiar with already are summarised briefly, and the special solar-technical requirements are detailed. There is some reference to earlier chapters in which the individual solar components are described. Any existing guarantee obligations with respect to earlier work by skilled tradesmen must be taken into account, particularly during work on the roof or the heating system.

4.1 A brief study of roofing and materials

4.1.1 The purpose of the roof

The principal purpose of a roof is:

- to provide spatial boundaries
- to carry the loads from wind, rain and snow by means of the roof skin
- to keep the weather influences out of the building
- to enhance appearance (shape, colour, material, surface structure).

See Figure 4.1. Because of ever-decreasing fossil energy resources and the evident climate changes, the roof will in future increasingly act as the main structure for supporting energy conversion elements: that is, solar thermal or photovoltaic systems. This means that the roof skin (and the façade) will be subject to significant changes in materials and appearance.

4.1.2 Types of roof

Roofs may be classified as follows, according to the inclination:

- flat roofs: up to 5° pitch
- pitched roofs: > 5° ≤ 45° pitch
- steep roofs: >45° pitch.

Numerous sub-types occur, for example with two slopes.

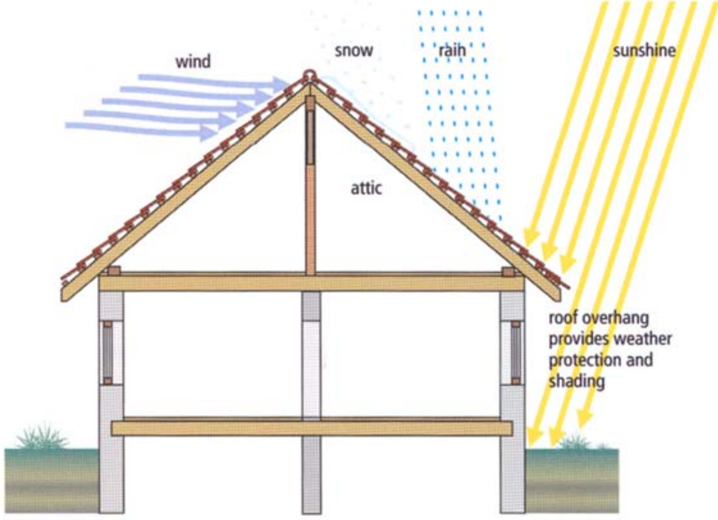


Figure 4.1. The purpose of the roof[26]

4.1.3 The components of the roof

4.1.3.1 ROOF STRUCTURES

This section describes some roof structures that are common in Europe. The list is not intended to be exhaustive.

- *Purlin and rafter*. In the case of roof truss purlins, the rafters rest on the purlins as inclined beams. The ridge purlin takes up the vertical loads and distributes them via the posts and struts; the base purlins correspondingly distribute them to the outer walls, and there may also be intermediary purlins. An extra purlin is sometimes required to attach the collector fixings. See Figure 4.2.
- *Rafter and collar beam*. In the case of the rafter roof, the rafters and the ceiling below them form a rigid triangle. There are no internal constructional elements. In the case of collar beam roofs, each pair of rafters is linked and stiffened with a so-called collar beam. See Figure 4.3.
- *Truss*. These are self-supporting structures (glued trusses, nail plate trusses etc.) and are increasingly found in new build. No changes may be made to trusses without the approval of the structural engineer. For cost reasons, truss roof construction is normally found only up to spans of about 17 m. See Figure 4.4.

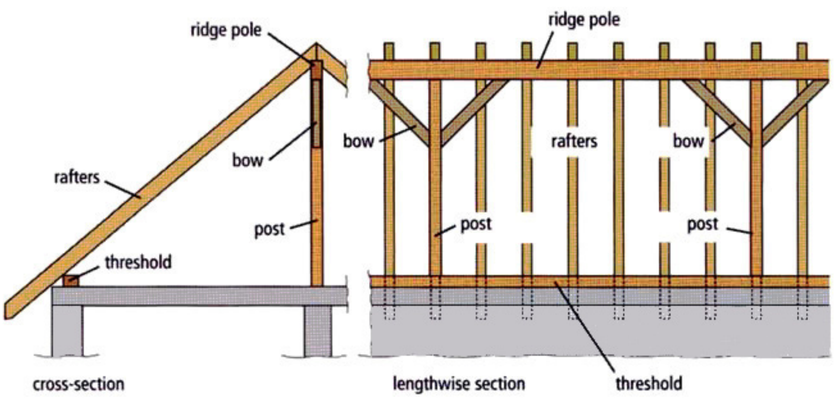


Figure 4.2. Roof truss purlins[26]

4.1.3.2 ROOF SKIN

A differentiation is made here between roof covering and roof sealing.

- *Roof covering*. This consists of individual elements such as tiles, concrete roofing bricks, fibrous cement slabs, bitumen shingles, slates and corrugated bitumen slabs. They must have a prescribed minimum roof inclination according to the type of overlap.
- *Roof sealing* (that is, flat roofs). This consists of, for example, bitumen roof sheeting, plastic roof sheeting, or plastic material applied in liquid form and then hardened.

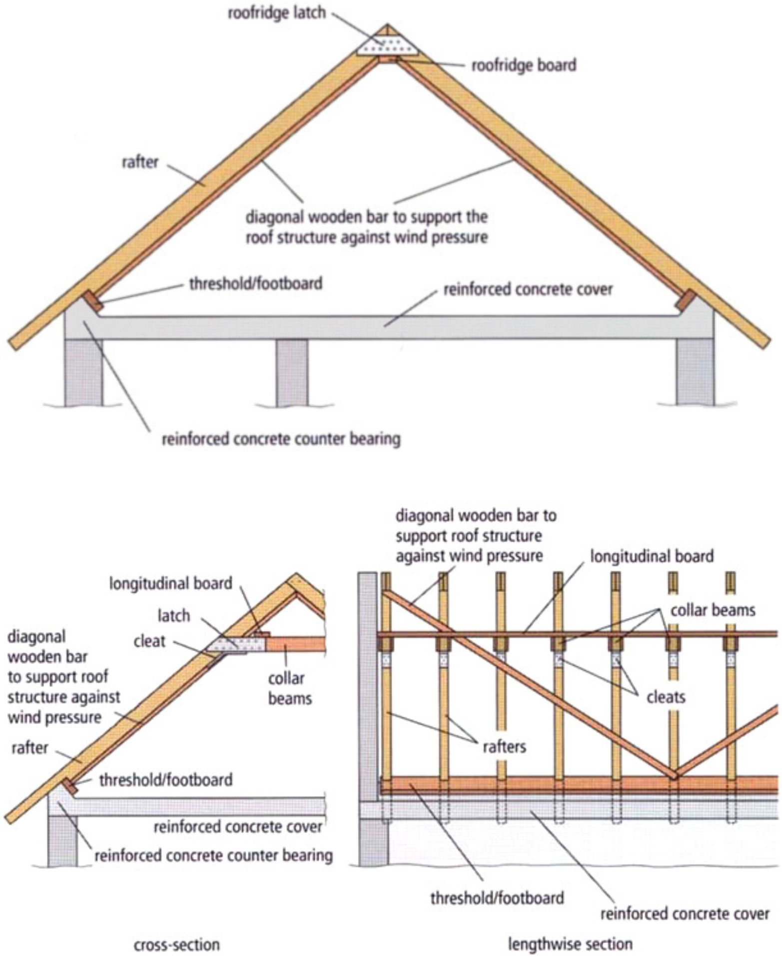


Figure 4.3.
Top: rafter roof truss. Bottom: collar beam roof truss[26]

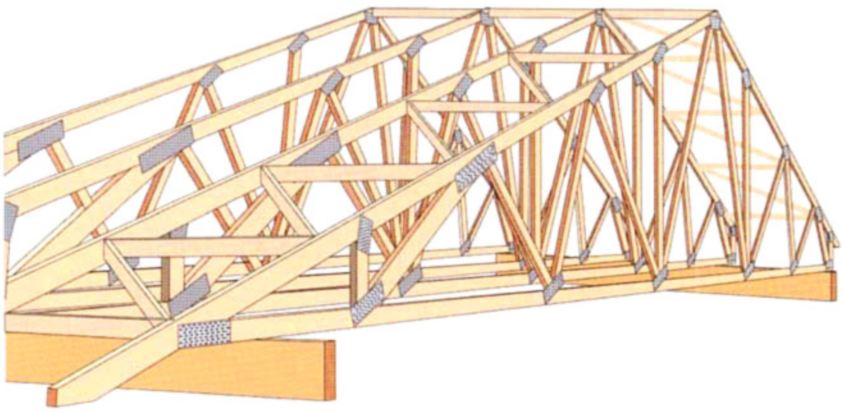


Figure 4.4.
Nail plate trusses[26]

Examples of roof coverings and seals are shown in Figures 4.5 to 4.8 and described in Table 4.1. Examples of moulded tiles, specials, roof hooks, snowguards, and walk-on gratings are shown in Figures 4.9 to 4.12.

Figure 4.5.
Left: pantiles. Right: wood shingles[27]


Figure 4.6.
Left: natural tiles. Right: plain tiles[27]


Figure 4.7.
Left: welded sheet installation on flat roof[28]. Right: plastic roof sheeting[29]


Figure 4.8.
Metal roofs[30]

Table 4.1. Types of roof covering and sealing

Type	Examples	Material	Type of fixing, processing	Notes
Tiles	Plain tile	Clay	Dry-laid, part-clamped, sarking felt or membrane, cemented	Good back ventilation, otherwise frost damage, medium to high breaking strength, efflorescence, mould formation
	Pantiles (single Roman), double Roman, interlocking	Concrete	Dry-laid, part-clamped, sarking felt or membrane, cemented	Surface weathering, high breaking strength, efflorescence
Slates	Slate I Slate II Circular shingling	Natural slates, stone slabs Fibrous cement[b] Bitumen	Nailed Nailed Nailed, clamped	Discoloration, weathering, low breaking strength RR[a] Shrinkage (when dry), swelling (when damp): drill holes must be larger, efflorescence (smears) RR[a],draws in moisture
Specials	Vents	Concrete, clay	Dry-laid	Can be offset
	Verge/eaves vents	Concrete, clay	Screwed	Impede installation of collectors
	Ridge tiles, bricks	Concrete, clay	Clamped (new build) Cemented (old build)	Impede installation of collectors
	Tiles with air pipe	Plastic, clay	Dry-laid	Impede installation of collectors
	Tiles with perforated base	Plastic, metal, clay	Screwed	Impede installation of collectors
	Special tiles with tread holders	Plastic, metal	Screwed	Impede installation of collectors
Flat sheet metal	Box section profile roof cladding Folded covers	Galvanized steel Zinc, titanium-zinc, copper, aluminium	Screwed, riveted Fixed with staples, folded	Zinc-plated box section plate, partially with added plastic coating, screws always in upper chord non-clamped folds, corrosion problems, good back ventilation, high thermal expansion, brittleness
	Ridge covers, chimney frame	Lead, zinc	Soldered, folded	
Profiled metal	Plastic-coated corrugation	Fibrous cement[b]	Screwed onto purlins	Not folded, water penetration through wind pressure
	Light corrugated sheets	Polyester	Screwed onto purlins	Not folded, water penetration through wind pressure
	Bitumen corrugated sheets	Bitumen	Nailed onto purlins	Not folded, water penetration through wind pressure
Liquid plastic	Roof impregnation, roof terrace sealing	Polyurethane, acrylate, resin	Cast, painted	Weather-dependent processing, carefully prepared background
Bitumen sheeting	Plastomer welded sheeting	Bitumen	Bonded, welded	Max. life 20 years, may be less than solar system, bitumen corrosion in connection with zinc plates
Plastic sheeting		EPDM	Connected with hot air	Contains plasticizer, brittleness, consider bitumen-compatibility
Organic roof	Thatched roof	Reeds, straw	Placed with wire on lathing	No known collector installation to date
	Grass roof	Film, substrate, special plants	Placed on roof	Only possible with stands

[a]RR = roofer is responsible
[b]Asbestos problem, special waste for these elements

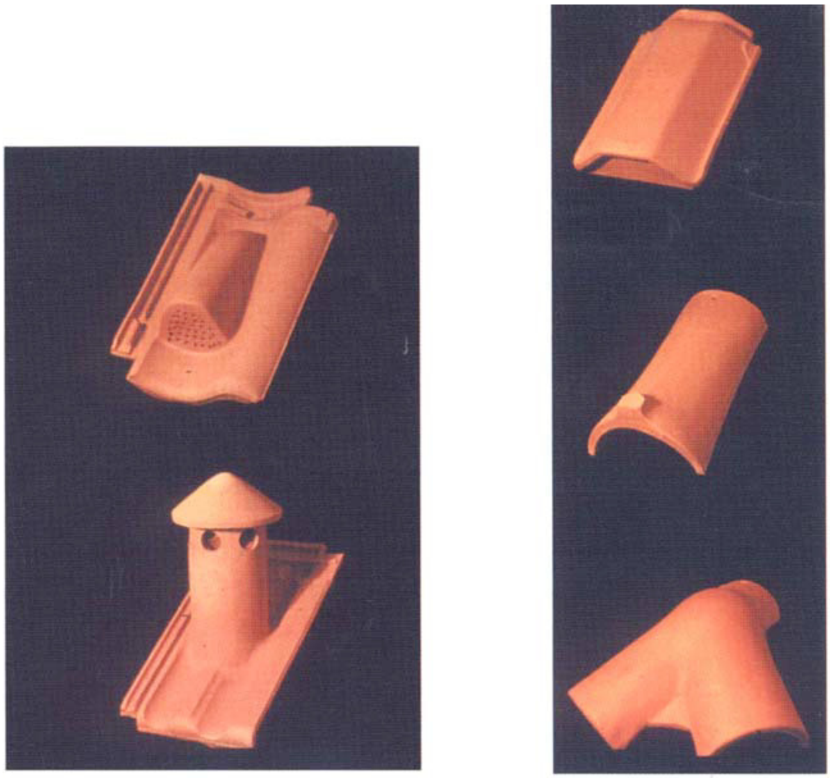


Figure 4.9.
Air tiles, vapour-escape pipes and various ridge tiles[27]

Figure 4.10.
Left: roof hooks. Right: step[30]

Figure 4.11.
Left: roof hooks. Right: walk-on grating[30]

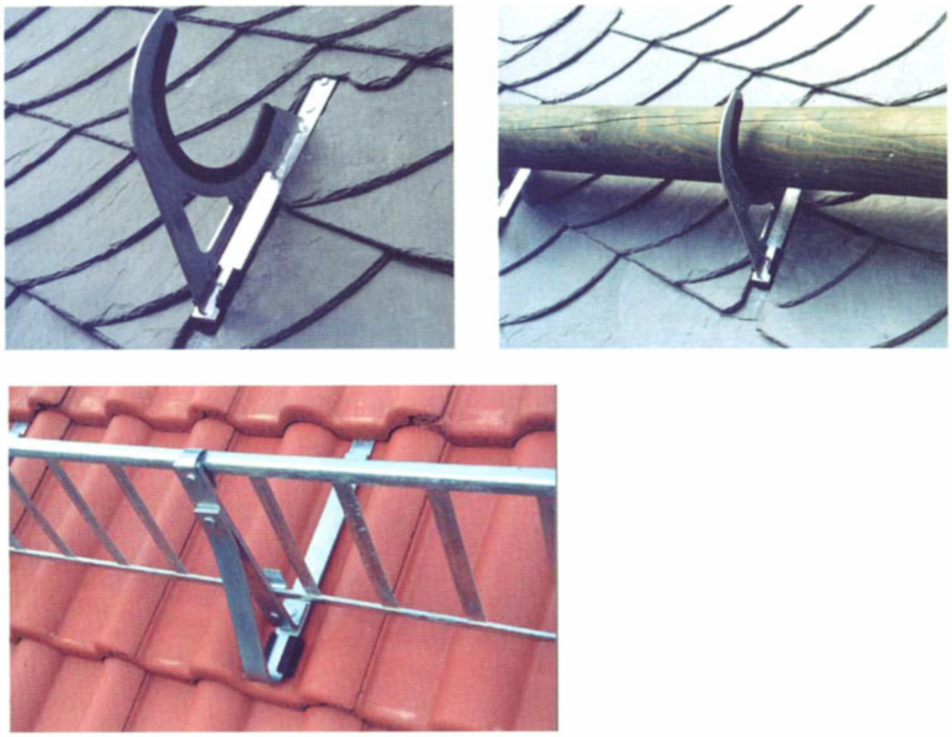


Figure 4.12.
Top: round wood holder.
Below: snowguard[30]

4.1.4 Pitched roofs

A pitched roof is often constructed as follows:

- rafters/thermal insulation
- roofing felt on formwork, otherwise sheeting beneath
- counter-lathing
- roof lathing
- tiles.

Thermal insulation can be installed in one of three ways:

- in the ceiling of the top storey
- between the rafters above head height
- over the rafters. (This is not shown in the figures: there are problems with fixing the collector, as in this case the standard parts cannot be used.)

4.1.5 Roof installations and mountings

During the installation of collectors the available roof surface can be restricted by the following features (Figure 4.13):

- room in roof
- dormer roof
- walk-in skylight
- chimneys, aerials etc.

4.1.6 Flat roofs

On can differentiate between a *cold roof* (thermal insulation under the boarding, ventilated in the intermediate space: see Figure 4.14), and a *warm roof* (thermal insulation above the boarding: see Figure 4.15). The problems of mounting collectors on warm roofs are described in section 4.3.3.2.

4.1.7 Materials

The materials used in the roof location for solar apparatus are subject to severe loads, which they must withstand over a long period, particularly if the system is expected to

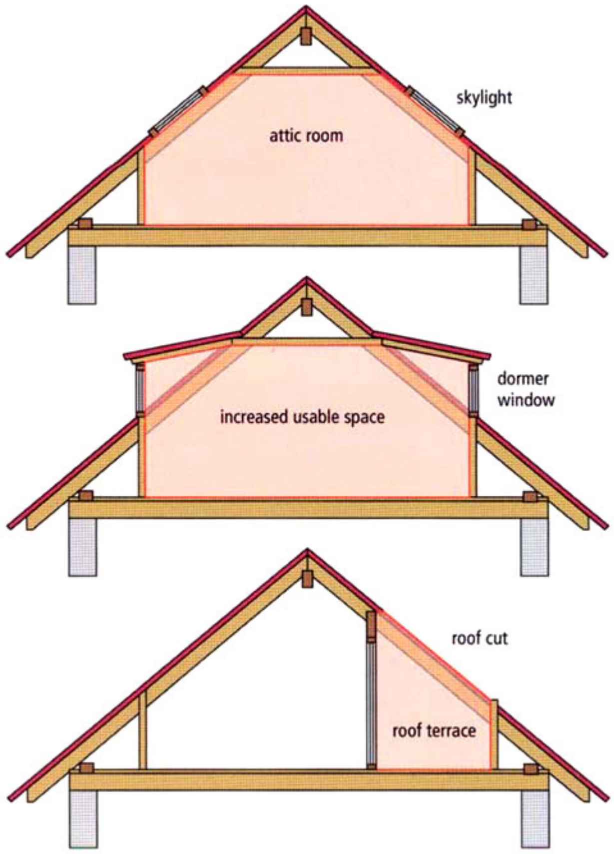


Figure 4.13.
Limitations to tilted roof mounting of collectors[26]

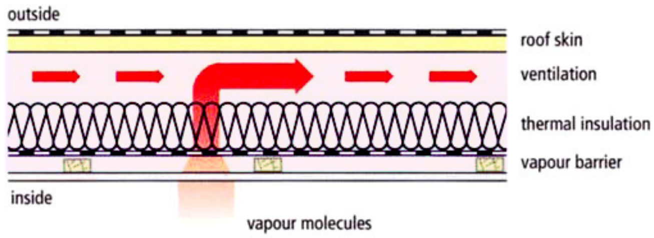


Figure 4.14.
Cold roof[26]

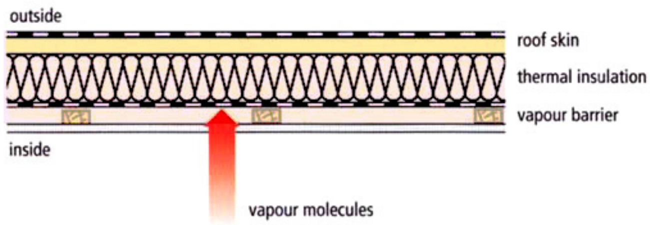


Figure 4.15.
Warm roof[26]

function and provide the predicted yields without faults for more than 20 years. The loads are:

- temperature variations between –15°C and 80°C (and within the absorber up to approximately 300°C)
- UV radiation
- rain, snow, hail
- wind forces
- bird and squirrel damage (in the case of external thermal insulation).

Table 4.2 lists the materials that are normally used:

Table 4.2. Materials used in roof mounting of solar apparatus

Material	Version	Application
Aluminium	Plain, anodized, powder coated, selectively coated	Collector frames, covering frames, bearers, rails, absorbers
Glass	Float glass, solar glass (prismatic, clear), anti-reflection glass, borosilicate glass	Transparent collector cover, glass cylinder and absorber pipes
Stainless steel	V2A (St 1.4301) chrome, nickel	Roof hooks, rails, screws, nuts, plates, collector frames, absorbers
Stainless steel	V4A (St 1.4571) chrome, nickel, molybdenum, titanium	Screws, nuts, plates
Steel	Galvanized	Roof hooks, rails, screws, nuts, plates, bearers, supports
Copper	Plain, selectively coated	Pipes, absorber strips, full-surface absorbers
Titanium-zinc plate	Plain	Aprons, flashing, soakers, rear wall of collectors
Lead	Rolled, zinc plated	Lead aprons, soakers
Wood	Glued wood Solid wood	Collector frames (in-roof mounting) Additional battens (in-roof mounting), boards for under-packing
Plastics	EPDM, PE, PP, PU rigid/flexible foam, mineral wood, silicon	Thermal insulation of pipes, collector, collector frame, sealing materials, adhesive.

THERMAL EXPANSION

Materials expand during heating and contract during cooling. (The exception to this is water, which has its greatest density at 4°C; with further cooling it expands again.) It is therefore necessary to take suitable precautions in order to absorb these length changes, otherwise damage can occur. The extent of the length changes depends upon:

- **the material**
- **the temperature difference.**

$$\Delta l = l_0 \times \alpha \times \Delta\theta$$

where Δl is the change in length (mm), l_0 is the original length (m), α is the expansion coefficient (mm/mK), and $\Delta\theta$ is the temperature difference (K).

EXPANSION COEFFICIENTS (mm/mK)

- **polyethylene: 0.2**
- **lead: 0.029**
- **aluminium; 0.024**
- **zinc: 0.02**
- **copper: 0.017**
- **stainless steel: 0.016**
- **steel: 0.012**
- **quartz glass: 0.001.**

EXAMPLE

Four collectors 2.1 m high and 1.2 m wide are installed vertically beside one another. The covering plate projects by 0.25 m on each side.

$\theta_{summer} = 70°C$, $\theta_{winter} = -14°C$

$\Delta l_{zinc} = 5.3 \text{ m} \times 0.02 \text{ mm/mK} \times 84 \text{ K} = 8.9 \text{ mm}$

$\Delta l_{al} = 5.3 \text{ m} \times 0.024 \text{ mm/mK} \times 84 \text{ K} = 10.7 \text{ mm}$

Hence the plate expands in total by about 1 cm. It must not be impeded (for example by solders), otherwise stresses and cracks could occur, and this would result in leaks. Therefore the plates are attached to the roof lathing with retainers or, in the case of zinc, with expansion pieces. For pipes, compensators or expansion bends are used.

Next Page

CORROSION

We differentiate between corrosion, corrosion signs and corrosion damage.

- *Corrosion (reaction).* This is the reaction of a metallic material with its surroundings, which leads to a measurable change in the material, and can lead to impairment of a metallic component or of a complete system.[31]
- *Corrosion signs (result).* These are the measurable changes in a metallic material through corrosion.[31]
- *Corrosion damage (possible consequence).* This is impairment of the function of a metallic component or a complete system through corrosion. Corrosion can lead to damage, but does not have to.[31]

EXAMPLE

Railway tracks can rust unimpeded in the free atmosphere. However, this does not impair their function; corrosion protection is not required. In contrast, steel radiators in an open heating system will rust because oxygen is continuously drawn in. If a hole occurs in a heater because of corrosion and water runs out, the function of this component – or even of the whole system – will be affected.

CORROSION PROTECTION

If two metals with different electrochemical potentials are in metallic contact, then, in the presence of water, the more base of the two materials will decompose. Therefore different metals should not come into contact with one another in a liquid circuit if possible. If this cannot be avoided in an individual situation, electrolytic separation by means of an intermediate electrical non-conducting material is recommended. Corrosion should particularly be expected if the more base of the two metals is downstream of the more precious metal. Small particles of the more precious metal can then be precipitated on the more base material and can lead to localised corrosion (or pitting). The flow rule must therefore be: copper – in the flow direction – after steel.

EXAMPLES

Roof area

In the flow direction of the rainwater, Cu ions from the copper chimney flashing dissolve a lower-lying aluminium covering frame, which leads to pitting. In contrast, an aluminium covering frame does not have any corrosive effect on a copper gutter beneath it.

Solar absorbers made of aluminium (for example Rollbond) can become unusable in a short time if the inhibitor is not sufficiently effective, or if they are connected to a copper pipeline.

Solar circuit

Steel pipes or fittings made of cast iron should never be mounted downstream of a copper pipeline. However, metallic connections of copper with copper–tin–zinc alloys (red bronze or brass) are unproblematic, because these alloys have a similar electrochemical potential to that of copper.[32]

The corrosiveness of glycol is suppressed by suitable inhibitors. These should be checked from time to time (see Maintenance, section 4.4.5).

Storage tank

Plain ferrous materials are subject to corrosion in water, which always contains oxygen, with the formation of non-protecting rust layers. Hence corrosion protection is necessary: for example, for the domestic hot water tank an enamelling process in connection with external current or magnesium anodes or a plastic coating.

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).

EXAMPLE

In soldering technology, use is made of this effect in the capillary soldering fittings. The liquid tin is drawn into the narrow gap even against gravity (solder gap width from 0.02 mm to a maximum of 0.3 mm, according to the pipe diameter).

However, there can be problems due to the capillary effect on the covering frames of in-roof-mounted collectors. Here, in the presence of unsoldered side panels, which overlap in the flow direction, water can penetrate.

Table 4.3 gives an overview of the techniques.

5 Large-scale systems

5.1 The fundamentals of designing the system size

5.1.1 Possible application areas

Large solar energy systems for water heating can be used in a multitude of buildings, which have either a corresponding domestic hot water (DHW) usage, a whole year's heating requirement, or both. For example:

- hospitals
- hairdressers
- old people's homes
- fitness centres
- holiday homes
- breweries
- camping sites
- laundries
- student lodgings
- dairies
- flats
- butchers
- schools
- bakers
- barracks
- large kitchens
- office buildings
- public houses
- sports complexes
- hotels
- indoor swimming pools
- showers in open-air swimming pools
- floor heating in stables
- agriculture (cattle troughs)
- car washing facilities
- lorry washing systems.

5.1.2 Initial data required for planning the solar system

Because of the varying provision of power and energy from the sun, knowledge of the consumption quantities, the consumption profile and the desired hot water temperature is required in the dimensioning of a solar energy system. These data then feed into the dimensioning task.

The values for hot water consumption given in the literature have been found to be too high in practice: their use often leads to over-dimensioning in the planning of solar energy systems. The consumption values are frequently old, and have been calculated with the objective of providing security of supplies. Determination of the required data for the consumption profile should, if possible, be carried out by long-term measurements of the hot water consumption. If this is not possible, or is too time-consuming, then the following method can be used for acquiring the consumption data and using them for calculations in simulation programs.

5.1.2.1 CONSUMPTION PROFILE AND QUANTITY

Data must be collected to differing extents according to the various potential users (see Table 5.1). For example, Figure 5.1 shows a typical questionnaire used to obtain the required data for hot water consumption.

Table 5.1. Examples of the data required for calculating solar thermal systems

	Daily	Weekly	Annual	Occupational profile seasonal	Strongly variable daily requirement for HW	Operating times of secondary HW circulation	Other users in times of low water consumption
Multi-family residences	X	X	X			X	
Administration buildings	X	X				X	X
Hotels, restaurants	X	X	X	X	X	X	X
Schools, sports halls	X	X	X	X	X	X	X
Sports complexes	X	X	X	X	X	X	X
Commerce, industry	X	X		X	X	X	X
Open-air swimming pools, indoor pool showers	X			X	X	X	X
Open-air swimming pools, indoor pool			X				X
Camping sites	X	X	X	X	X	X	X

The consumption profile data thus obtained are used, for example, in simulation programs to calculate the system yield and behaviour. For this purpose the data are inserted as a table into the simulation program. Alternatively the different simulation programs offer consumption profiles for different buildings and user groups.

In order to permit planning where there is no possibility of measuring the water consumption, or in the event of uncertainties, it is possible to access standard published DHW consumption data of buildings. The following rule-of-thumb values have been determined for multi-family residences in many countries:

> 20–30 l (at 60°C) per day per person (which is roughly equivalent to 30–50 l per person per day at 45°C; see Chapter 3, sections 3.5.2.4 and 3.5.2.5).

Moreover, the occupation of the flats (one dwelling unit = average 3½ persons) must be examined in more detail if possible. In one example a consumption of 40 l per day per person and average occupation of 3 people was assumed. The actual consumption however, instead of the estimated 120 l per day per flat, was in fact only 45 l per day per flat when measured. Obviously this led to far too large a solar water heater.

5.1.2.2 REQUIRED HOT WATER TEMPERATURE

Of great significance for the future energy yield of the solar system is the target domestic hot water temperature of the application. The lowest temperature level likely to be required is 25°C for heating the water in cattle troughs. In one/two-family homes (and also some production applications) 45°C is sufficient. However, in many countries drinking water regulations require higher temperatures. Larger buildings usually require a temperature of 60°C at the storage outlet. Wherever it is reasonable and safe within regulations, the domestic water heating should be restricted to the lowest possible temperature level in order to save energy.

The heat yield of the solar collector and the whole system significantly increases with a reduction in the required temperature in the collector circuit. A reduction in the water temperature generated by the sun causes a distinct increase in the energy yield per m^2 of collector per annum in the entire system.

5.1.3 System planning and design

At the beginning of the planning phase, rough figures on the dimensions of the most important system components – that is, the collector field and heat stores – are required for the preliminary planning and cost estimate. For dimensioning purposes there are different target sizes. The systems are designed either for a particular solar fraction using existing structural conditions (for example the size of the roof, or the

1. Description (Indicate one)

One family home	☐	Multifamily residence	☐		
Refectory	☐	Student lodging	☐	Old-peoples' home	☐
Hotel	☐	Restaurant	☐	Camping site	☐
Nursery	☐	Sports hall	☐	School	☐

Other (Add description)..

2. Hot water consumption profile

State peak consumption*: litres/hour at temperature °C
or persons/hour**

*Assume DHW is mixed down to 38°C at appliance ** valid for showers

% of daily total	Mon	Tue	Wed	Thur	Fri	Sat	Sun	Example
Between.......o'clock to............ .o'clock								20%
Between.......o'clock to............ .o'clock								40%
Between.......o'clock to............ .o'clock								25%
Between.......o'clock to............ .o'clock								15%
Total daily consumption in litres (= 100%)								1000 l

If each month is the same, write 100% = normal consumption. Otherwise indicate % days in month absent i.e. holidays

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Consumption in %												

Secondary domestic hot water circulation (indicate one): Yes No
Running times: From ...... o'clock to ...... o'clock and from ...... o'clock to ...... o'clock and from ...... o'clock to ...... o'clock and from ...... o'clock to ...... o'clock

Total existing hot water consumption: State if calculated or measured: .... l/annum

3. Special factors

Base consumption (e.g. caretaker's flat or other) .... persons

Total no. of showers:	Total no. of shower cubicles:............
Max. water flow per shower: ...... l/h	Max. water flow per cubicle: .... l/h
Type of shower (select as many as apply):	Coin-operated:
	Timer controlled:
	Hand operated:
Hot-fill dishwashers/washing machines:	Consumption:. ...... litres/day

Hotel

Overnight rooms:
Single rooms: ...... with showers: .... and washbasins:....... and baths: ....
Double rooms: .... with showers: .... and washbasins:....... and baths: ....
.... bed rooms: .... with showers: .... and washbasins:....... and baths: ....

Restaurant

Capacity: .... persons Breakfasts:.........../week Lunches:......../week
Evening meals: ..../week .... toilets with in total .... hot water washbasins

Figure 5.1. Questionnaire template to establish hot water consumption

size desired by the customer), or for the highest possible energy yield per square metre of collector field.

For example, the owner of a one-family home may prefer to procure a solar system with a high solar fraction so that in the summer he or she can enjoy solar-heated water with the heating boiler turned off. The administrator of a multi-family residence, who would rather keep the operating costs low, asks the designer for a low solar heat price and hence low costs per square metre. Another investor, with a restricted budget, might prefer to achieve high primary energy substitution. As preheating systems achieve higher system utilization in this case, two preheating systems in two of his houses fulfil this requirement better than one solar system with a high solar fraction on one of the houses.

During client discussions, solar systems with high system utilization and the resulting high kWh yields per square metre of collector field are often stated to be the aspired objective. On the other hand, solar energy systems with high solar fractions are unjustifiably described as over-dimensioned. Both design variants are equally good if the prescribed objective (the brief) is achieved by the planning. A deviation from the expected yields that is due to incorrect consumer figures or a later change in the hot water requirement can also not be blamed on the solar system. What is decisive in the assessment of the function or performance of a solar thermal system is comparison of the actual yields with the results of simulation calculations on the basis of the actual hot water consumption.

5.1.3.1 DESIGN OBJECTIVE: HIGH PRIMARY ENERGY SUBSTITUTION

In order to achieve the greatest possible saving of conventional fuels in the project under consideration (that is, high primary energy substitution), the degree of solar coverage in the whole system must be selected to be as high as possible. Such a design is frequently sought in the case of smaller solar systems for one- and two-family homes, or in solar systems for space heating. In temperate climates, for a desired solar fraction for domestic water heating above 60%, the conventional heating can be put out of operation in the summer, which can contribute greatly to the satisfaction of the operator and to avoiding stand-still heat losses in the heating boilers. In larger solar systems, a degree of solar coverage of 50% should be targeted to achieve the design objective.

In tropical climates a solar coverage of 75–100% can be chosen.

5.1.3.2 DESIGN OBJECTIVE: LOW SOLAR HEAT PRICE

Decisive for the efficiency of the solar system is the highest possible system utilization, which leads to a high (specific) kWh yield per square metre per annum. As already described, high system utilizations are achieved with low solar fractions. These systems are also described as *preheating systems*. As this type of system usually achieves only preheating of the domestic water, even in the summer, the conventional heating system remains in operation for the full year. In temperate climates the degree of solar coverage for this design objective is between 10% and 45%; for further considerations it will be assumed to be 25%.

In tropical climates this is a less logical option unless the load is irregularly distributed over the year (for example, the holiday season for a hotel). In such cases, custom calculations need to be made.

5.1.3.3 DESIGN WITH THE HELP OF AN APPROXIMATION FORMULA

Starting point values are given in Table 5.2 for dimensioning the collector field and storage tank sizes. The following factors are used for this:

- a hot water temperature of 60°C
- continuous domestic warm water draw-off

Table 5.2. Approximation formula for dimensioning collector fields and storage tanks for two types of climate

	Temperate climates (1000 kWh/m²a, pronounced seasons)		**Tropical climates (2200 kWh/m²a, evenly spread over the months)**
	Solar fraction 25%	**Solar fraction 50%**	**Solar fraction 80%**
Collector surface area	0.5 m² per 50 l HW consumption (60°C) per day	1.25 m² per 50 l HW consumption (60°C) per day	0.6 m² per 50 l HW consumption (60°C) per day
Storage tank size	30–50 l tank volume per m² of collector surface	50–70 l tank volume per m² of collector surface	40–60 l tank volume per m² of collector surface

- location with average solar radiation (approximately 1000 kWh/m^2)
- south alignment of the collector field and a setting angle of 40°.

The values apply to flat collectors with good performance ($\eta_0 = 0.8$, $k_{eff} < 3.5\ W/m^2K$). System-related data must then be determined on the basis of building-specific simulations. Further simulation calculations are then required to convert to different temperature levels. The store volumes should be dimensioned fairly generously within the scope of the economic options and the space available.

Detailed building-related design should take place with the aid of recognized simulation programs (see Chapter 10).

5.2 Systems

5.2.1 Systems with domestic water store(s)

The simplest systems for solar energy systems with up to 30 m^2 of collector field are one or two-store systems with domestic water stores and the option of thermal disinfection. The design of the stores corresponds with those in a one or two-family home. As an alternative to immersed heat exchangers providing auxiliary heating, it is possible to use an external store-charging unit (see Figure 5.2). This auxiliary heating method also permits thermal disinfection of the whole domestic water storage system. It has the following advantages and disadvantages compared with systems with buffer storage tanks:

ADVANTAGES

- simple system design
- best utilization of low collector temperatures
- fewer system components
- low costs if materials are sensibly selected
- no need for discharge regulator or heat exchangers.

DISADVANTAGES

- lower heat yields because of thermal disinfection
- under certain conditions domestic water stores may involve higher costs than buffer storage systems.

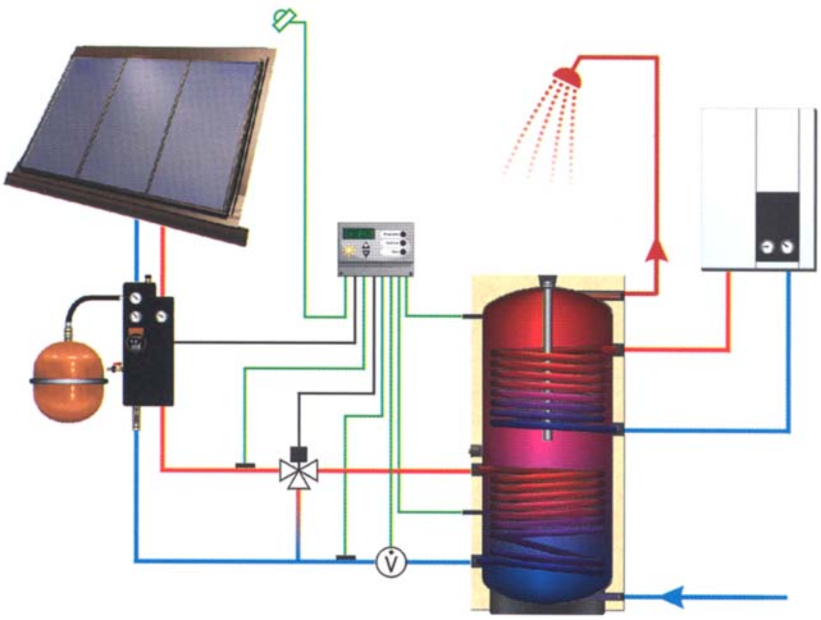


Figure 5.2. Solar energy system with domestic water tank and the possibility of thermal disinfection

Thermal disinfection brings the whole storage system to a high temperature level. In order to minimise the solar yield loss, this should be done in the late afternoon just before a large amount of warm water is drawn off. This ensures the lowest possible storage temperatures in the evening and on the following day, which permits the system to switch on at the earliest possible time next morning. With this system size, both immersed and external designs of heat exchanger can be used.

As the domestic water is heated by the solar system via an internal heat exchanger, a further heat exchanger can be dispensed with, compared with a system with intermediate buffer storage tanks. Thus there are lower temperature losses (temperature difference in the second heat exchanger). In the lower part of the domestic water store, the cold water temperature orientates itself to that of the domestic water supply. In this way the solar energy system can make its contribution even at low temperature levels, and thus achieve high yields.

The need for such thermal disinfection measures is obviously strongly dependent on local drinking water regulations. As thermal disinfection brings about extra energy consumption, it should be avoided when regulations allow.

5.2.2 Systems with thermal buffer stores

An increase in the temperature level in the whole domestic water storage tank automatically leads to higher energy losses in the system considered. With large domestic water stores that serve as solar energy storage systems the losses are greater than in conventional systems for hot water heating with correspondingly smaller stores. Moreover, heating of the energy store leads to a reduction in the collector circuit utilization because of the heat losses associated with the higher temperatures. The energy yield may decrease to an extent of 15% with boundary conditions that are otherwise the same.

Common to the systems described in this section is the fact that the heat gained in the collector circuit is first stored in a buffer thermal store, and is led to the domestic water store only when required. In order to obtain a high system yield, similar to those for systems with more direct energy storage, the system variants described in the following sections are used.

The use of external heat exchangers and – with the exception of stratified stores (and their internal charging) – the type of charging is also common to the systems.

When a minimum solar radiation is reached, the collector circuit pump first starts and heats up the collector circuit. If a useful temperature then exists at the entry to the collector circuit heat exchanger, the buffer circuit charging pump is switched on, and the buffer tanks are charged by means of a switching system, for example a three-way valve or a stratified-charging device in the buffer tank.

5.2.2.1 BUFFER STORAGE SYSTEMS USING THE STORAGE CHARGING PRINCIPLE

If the temperature in the hotter buffer storage zone (the right-hand buffer store in Figure 5.3) reaches a useful temperature level for heating the domestic water in the standby store, then the buffer circuit charging pump and the DHW store-charging pump are engaged. Ideally, the DHW store should be divided into a standby zone for auxiliary heating and a (lower) zone for charging by the solar system.

The upper standby zone is held continuously at the temperature level required for safe supply by the conventional auxiliary heating. Taking account of regulations, the whole domestic water storage area can be thermally disinfected (not shown in the figure). In this way top-up heating of the domestic water and thermal disinfection are carried out exclusively in the DHW store by conventional heating. In comparison with the different concepts for auxiliary heating of the domestic water to the required withdrawal temperatures, this has proved to be the most expedient with respect to the maximum utilization of the solar system.

ADVANTAGES

- Discharging of the buffer tank is possible independently of the current water consumption (see section 5.2.2.2).
- High system utilization is achieved for the whole system with auxiliary heating only in the domestic water tank (the solar zone is not heated via the auxiliary heater, and is always at the lowest possible temperature level).
- The discharge heat exchanger can be kept relatively small and inexpensive.

DISADVANTAGES

- The DHW store requires a solar zone in the lower area, or the temperature of the auxiliary heating must be reduced to allow charging by the solar system even at lower temperature levels.

- The discharge of the buffer storage tank must be controlled so as to keep temperatures as low as possible in the bottom zone of the colder buffer tank.

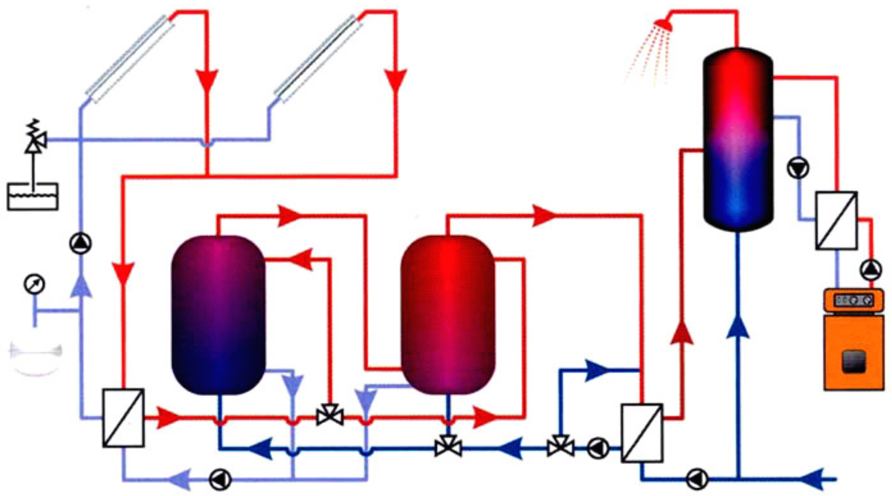


Figure 5.3. Buffer storage system using storage charging principle; top-up heating in the standby tank

5.2.2.2 BUFFER STORAGE SYSTEMS USING THE ONCE-THROUGH-FLOW PRINCIPLE

With this type of system (Figure 5.4) the buffer thermal store is discharged using the once-through-flow principle. When domestic water is withdrawn, and if at the same time a useful temperature level exists in the hotter buffer, this is then discharged via a circuit pump. The solar heat is then transferred to the domestic water. By controlling the volumetric flow in the discharge circuit, the buffer water can thus be cooled to, for example, 5 K above the cold domestic water entry temperature. The precondition for this, however, is very accurate matching of the volumetric flow in the buffer tank discharge circuit to the momentary withdrawal volume, which requires precise and rapid control systems.

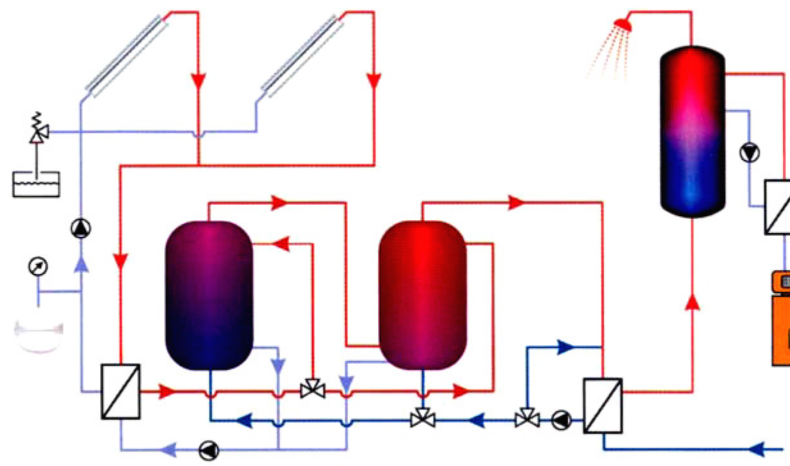


Figure 5.4. Buffer storage system using the once-through-flow principle

Cooling of the buffer tank water is possible for both small and large withdrawal rates, and the colder buffer storage zone thus takes on the lowest possible temperatures. The solar yield is increased because of the heat transfer from the solar circuit at this low temperature level.

ADVANTAGES

- Existing domestic water tanks can continue to be operated unchanged after the installation of the solar system. Even pure once-through-flow systems can be supplemented by a solar system.
- The solar system can be linked very easily into the existing domestic water network through the installation of the discharge circuit heat exchanger.
- A higher solar yield can be achieved through the cold return to the buffer tank if the discharge controller operates perfectly.

DISADVANTAGES:

- Control of the discharge must operate very accurately; in practice this does not usually happen.
- If the withdrawal rates vary considerably and the buffer tank volume is very high, the once-through-flow system becomes sluggish and cannot supply sufficient heat from the buffer.
- The discharge circuit heat exchanger must be designed for medium or maximum withdrawal peaks, and is thus large and expensive.
- Heat exchangers cause pressure losses, which lead to pressure variations in the domestic water supply with changing withdrawal rates, which can cause unpleasant temperature variations with mixer taps.

5.2.3 Integration of circulation systems

See Figure 5.5. In order to use solar heat to cover the heat losses of a circulation line, the following general conditions should be observed:

Again, drinking water regulations greatly influence the temperature regime at which circulation systems are and should be operated. In general, temperatures of >55°C are to be maintained. This temperature level is led back into the DHW store at a given position. Depending on the running time of the secondary circulation, a temperature increase may occur in the colder zone of a store. In addition, this circulation leads to a mixing process that also results in a lower solar yield.

Heating up of the (lower) solar zone of the store by the circulation circuit should be avoided as far as possible. The temperature level, which is significantly higher than the cold water temperature, would otherwise lead to a strong reduction in the collector circuit utilization.

For preheating systems (or systems with low solar fractions) in connection with secondary circulation and a return of >55°C, the linking of a circulation circuit into the solar system makes little sense. In a solar system with a low solar fraction, a temperature level >55°C is achieved on only a few days in the summer, which makes coverage of the circulation losses at this temperature level practically unnecessary.

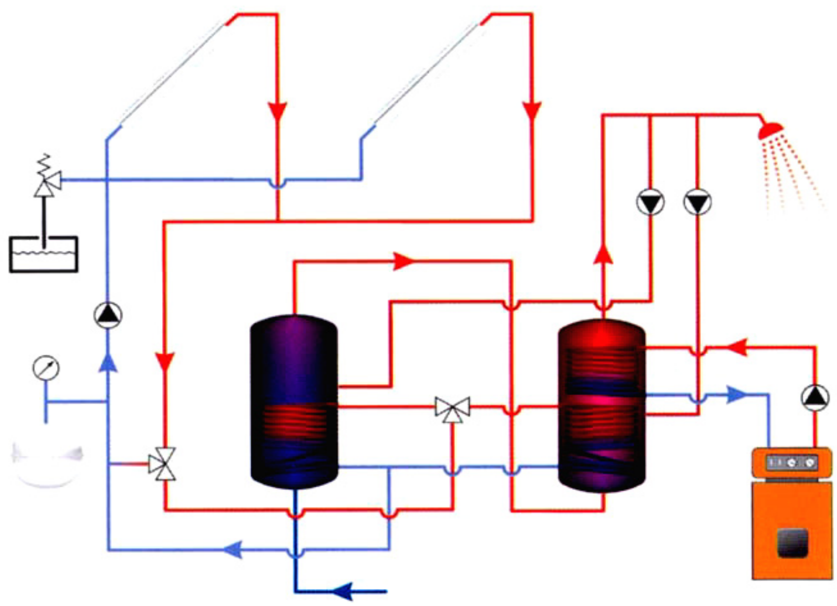


Figure 5.5. Integration of the circulation circuit, according to temperature, into either the middle of the height of the left-hand preheater tank or the right-hand standby tank

5.3 Control of the systems

Basically, in solar systems with buffer stores two systems have to be controlled and regulated:

- the collector circuit/storage charging circuit
- the store discharge circuit.

For simplification purposes, instead of differentiating between regulation and control in the following, the term 'control' will be used.

5.3.1 Collector circuit/storage charging circuit

5.3.1.1 BASIC FUNCTION

See Figure 5.6. If there is a useful temperature difference between the collector field and the solar store, the collector circuit pump and possibly the store-charging pump are switched on, and the store is charged. If store charging is no longer possible owing to a decrease of the temperature difference, the controller switches off the pumps, and unwanted discharging of the solar store via the collector field is thus prevented. Almost all control concepts are based on the principle of temperature difference measurement and on corresponding programs for controlling the different systems.

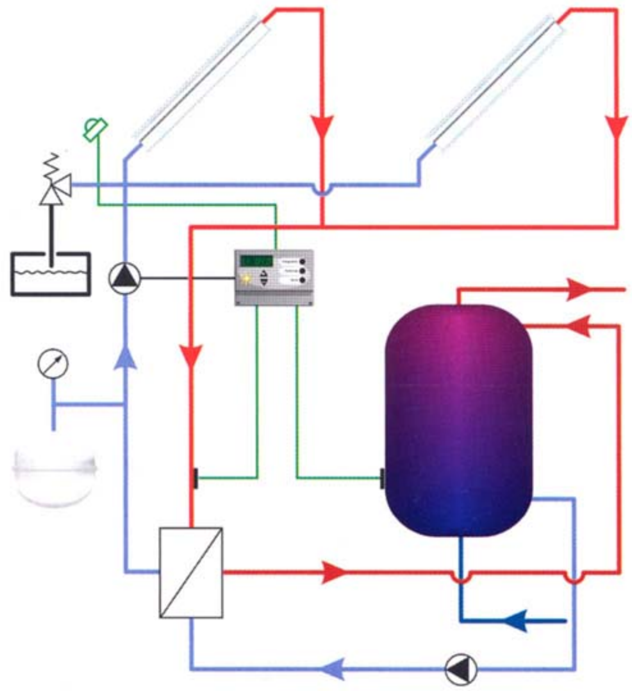


Figure 5.6.
Control of storage tank charging

The heat exchangers used in the collector circuit also influence the switching of the pumps. A small heat exchanger in the store with a reducing temperature difference between the heat transfer medium and the store can only supply an ever-smaller heat quantity to the storage water. In spite of higher temperatures in the collector, the controller must switch off the collector circuit pump in this case to avoid inefficient circulation around the collector circuit. It is therefore necessary to adapt the switch-off temperature difference to the heat exchanger performance.

5.3.1.2 CONTROL STRATEGY

Most systems and control concepts found on the market today follow the strategy of charging the solar store when an adjustable temperature difference between the collector field (or feed temperature on external heat exchanger) and the store (temperature in the lower zone) is reached. Thus, in systems with DHW storage, charging from the collector circuit starts for example as early as from a temperature of 13°C in the collector (8°C cold water entry plus 5 K temperature difference). During charging, this temperature level increases until the maximum storage temperature (60–95°C) is reached.

The collectors, circuits and heat transfer medium have a given heat capacity. The longer the lines in the collector circuit and the greater the pipe diameter, then the greater the heat capacity in the collector circuit. The system inertia therefore increases. In systems of the size under consideration it is usual to first allow the collector circuit to 'run up to heat' via a bypass circuit (this avoids cooling of the store). The bypass circuit is not used in small solar systems with short line paths because of the lower heat capacities in the collector circuit.

5.3.1.3 BYPASS CIRCUIT WITH IMMERSED HEAT EXCHANGER AND THREE-WAY VALVE

Apart from the collector circuit pump, the collector circuit controller also manages a three-way valve (Figure 5.7). Until a useful temperature is reached at the line just before the inlet to the store, the collector circuit is switched to bypass operation and is led past the store heat exchanger. This switching system is used only in connection with immersed heat exchangers.

5.3.1.4 BYPASS CIRCUIT WITH EXTERNAL HEAT EXCHANGER AND TWO PUMPS

Apart from the collector circuit pump, the collector circuit controller can also manage the storage circuit charging pump (Figure 5.8). Until a useful temperature is reached at the line shortly before the inlet to the external heat exchanger, only the collector circuit pump is operating. If the useful temperature is reached, the storage circuit charging pump starts to operate.

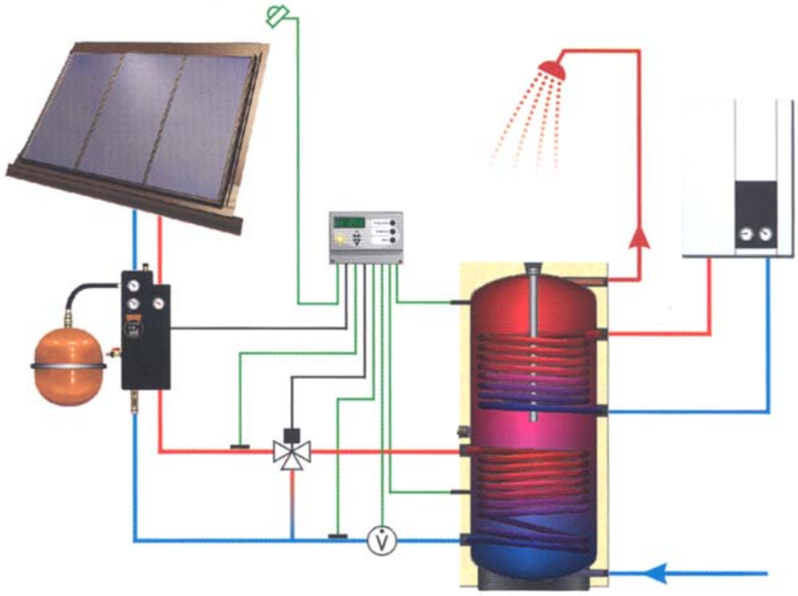


Figure 5.7.
Bypass circuit with three-way valve

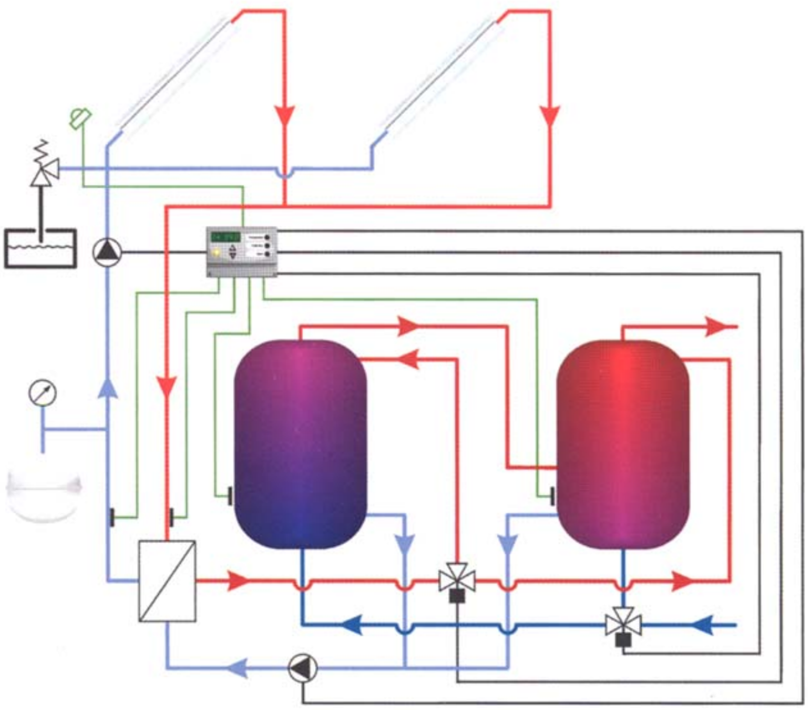


Figure 5.8.
Bypass circuit with separate control of collector and buffer tank circuit pumps

This variant is examined in more detail below, in view of the widespread use of external heat exchangers

CONTROL OF THE COLLECTOR CIRCUIT BY MEANS OF RADIATION AND TEMPERATURE SENSORS

A radiation sensor can be attached to the collector field and connected to the collector circuit controller. With sufficient solar radiation, the collector circuit pump is started up. To start the pump it is advisable to compare the measured radiation value with the store temperature. During system operation, the controller continuously gathers information on the activity of the collector circuit pump with corresponding radiation values as well as the store temperature. For instance, at a store temperature of 50°C, the collector circuit pump does not start up until the solar radiation exceeds 500 W/m^2; at a store temperature of 10°C, the pump switches on as early as at 150 W/m^2; and so on. This avoids having the collector circuit pump start up at a solar radiation level that is too low for further charging of the store. Moreover, the controller is matched to the changed gain and loss variables in the collector circuit through the continuous gathering of the new temperature and radiation values.

If the heat transfer medium in the collector circuit at the temperature sensor in front of the heat exchanger inlet reaches a useful temperature difference of $\Delta\theta$ = 2–5 K above the store temperature, the charging pump is started. If $\Delta\theta$ falls below 1–3 K the buffer circuit charging pump is stopped. Moreover, if the intensity of the sun's radiation measured at the radiation sensor decreases below a threshold, the collector circuit pump is also switched off. The system is not restarted until the intensity of the sun's radiation increases again.

If the collector circuit pump is started at a fixed value, for example 130 W/m^2, this can lead to extremely long operating times of the pump without yields. For example, the solar radiation can be just slightly above this value for the whole day but the collector will still not reach a useful temperature level. Also, when the store is already very hot, a renewed starting of the collector circuit pump in the bypass can be pointless (for example, if the sun comes out after an afternoon shower, the collector temperature will not exceed the store temperature even by late evening).

Shading of the radiation sensor must be avoided. For example, the solar cell can be put out of action by bird droppings: this type of fault should be considered in the case of defects.

CONTROL OF THE COLLECTOR CIRCUIT BY MEANS OF TEMPERATURE SENSORS

The collector circuit pump can be switched on if the temperature at a temperature sensor in the collector is 5–7 K above the temperature at the lower store sensor. If a temperature of 2–5 K above the store temperature is measured at the sensor in front of the heat exchanger inlet, the store-charging pump is also started. If the temperature difference falls below 2–4 K the pumps are switched off one after the other.

5.3.1.5 STORAGE TANK CHARGING AT DIFFERENT TEMPERATURE LEVELS

See Figure 5.9. To achieve useful temperatures in the stores rapidly, they should be divided into different temperature levels. This can be done by series connection on the discharge side, in which the store is charged alternatively into the cold or hot storage area. With the use of valves and pumps to control the different tanks the temperature levels should be limited to two, independently of the system size, as with the increasing use of pumps and valves the susceptibility to faults also increases greatly, without the solar yield being significantly increased.

Charging of the two levels can alternatively take place by means of a three-way valve or a second charging pump. After a useful temperature for charging a storage level has been measured at the temperature sensor in the collector circuit in front of the heat exchanger inlet, the three-way valve is opened at the corresponding charging level. With the use of two storage tank charging pumps instead of the three-way valve the corresponding storage tank charging pump is started to charge the usable level. A priority storage area (charging level) is usually defined in the controllers for charging. This charging level is then loaded as a priority, and only if no further temperature increase is possible is the second charging level used.

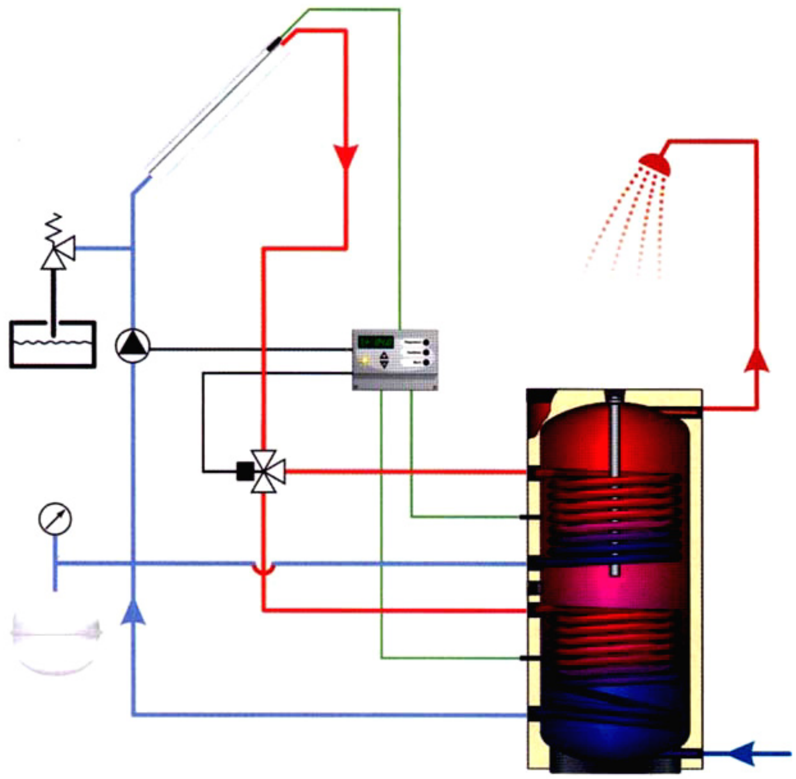


Figure 5.9.
Charging a storage tank with different temperature levels (immersed heat exchanger)

5.3.1.6 STORAGE TANK LOADING IN THE CASE OF TANKS WITH STRATIFIED CHARGING EQUIPMENT

See Figure 5.10. When using layer charging equipment it is also possible to charge several stores in a series-connected system. The heated water always exits through the charging equipment in the warmer store at the charging level corresponding to its temperature. In this way, in the case of high temperature levels the warmer store is charged in the upper area. If the charging temperature level falls, the heated water exits the charging equipment at ever-lower levels. If the temperature level of the loading circuit in the warmer tank can no longer be used, the water is fed into the corresponding temperature level of the second (colder) tank via the alternative route of the lowest layer.

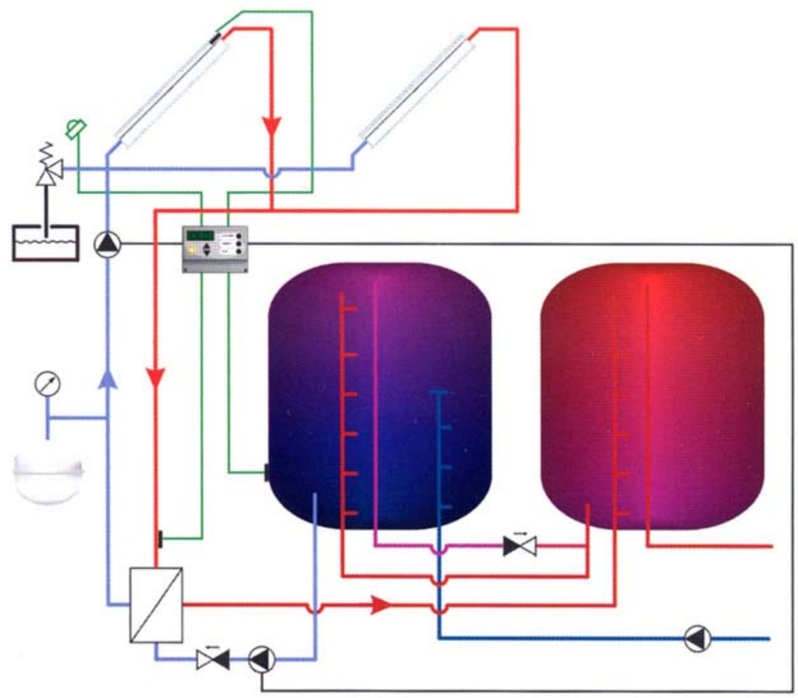


Figure 5.10.
Storage tank loading for tanks using stratified charging equipment

This storage loading system requires a controller that has been especially matched. This only measures the temperature in the coldest tank; charging of the different levels takes place automatically through the layer charging equipment without the use of further valves or pumps (see also Chapter 2, section 2.3.2.1).

5.3.2 Buffer tank circuit discharging

According to the discharging strategy, correspondingly adapted control concepts are used according to either the storage charging principle or the once-through-flow principle.

To avoid possible limescale build-up in the discharge heat exchanger of the buffer storage system and, moreover, to establish a maximum temperature for the design of the heat exchanger, the temperature in the inlet of the discharge heat exchanger is limited for example to 55°C (but taking into account drinking water regulations). This takes place through a mixing process by a thermostatic mixing valve in the inlet or a mixer in the return line from the heat exchanger. The thermostatic mixing valve is set to the desired maximum inlet temperature to the heat exchanger. The three-way valve or the three-way mixer in the return line is controlled by means of a fixed-value controller or, for smaller systems, also by a thermostat head with remote sensor. The accuracy of the controller thereby depends on the running time of the valve/mixer and the speed of the signal processing in the fixed-value controller. For systems with discharge controllers for controlling the once-through-flow principle, which react very quickly, the feed restriction is therefore often dispensed with, as its control speed is too low in comparison with the discharge regulation.

5.3.2.1 ONCE-THROUGH-FLOW PRINCIPLE

The objective of this principle is the best possible cooling of the buffer water during discharging or the maximum temperature increase in the domestic water. To meet both objectives the volumetric flow of the discharge circuit must be matched to the (variable) volumetric flow of the domestic water circuit. This is done by cycling (or speed controlling) the discharge pump.

The discharge controller measures the temperature difference between the top of the (warmest) buffer tank and the cold water. If the buffer is 2–5 K warmer than the cold water entry, the pump for the buffer discharge circuit is started up at, for example, 10% of its nominal flow rate. In this way the inertia of the discharge circuit is first overcome, and a useful temperature is achieved in the discharger heat exchanger for immediate use at the hot water taps. The controller monitors the flow in the domestic water circuit. If a flow is measured here the buffer discharge pump is started and the volumetric flow from it is regulated according to the criterion 'coldest possible return flow'. For this purpose, with the discharge pump running, the temperature difference is measured between the entry temperature of the cold water and the exit temperature of the return flow.

If the buffer circuit discharge pump is cycled by the controller (or is speed-regulated), a selectable temperature difference is set up between the cold water entry and the return flow of the buffer discharge circuit of, for example, 5 K. The buffer circuit can thus be discharged down to the temperature of the cold water entry plus 5 K.

For this control variant it is necessary to use precise and fast-reaction sensors. Moreover, the controller must possess high scanning rates when acquiring measured values. The sensors must be installed according to the manufacturer's instructions using immersion sleeves. To avoid pressure losses or possible error sources the measurement of the flow should take place if possible in the domestic water circuit by means of temperature comparisons instead of flow monitors or the like. Additional manufacturer's instructions concerning the positioning of sensors must be taken into account with respect to the yields.

Note: In practice these systems do not usually operate without faults. They should therefore only be used in discharge units that have been preconfigured by the manufacturer. In any case great care is necessary when installing them.

5.3.2.2 STORAGE TANK CHARGING PRINCIPLE

The discharge controller compares the temperatures in the (warm) buffer and in the bottom area of the domestic water store. If the temperature in the buffer is 2–5 K higher, the pumps are started to discharge the buffer. If the temperature difference falls below 1–2 K both pumps switch off.

During charging, the temperature in the domestic water store increases and hence also in the buffer discharge return. To avoid too severe an increase in the return flow temperatures in the buffer discharge, the temperature in the lower zone of the domestic water store is often limited. To discharge the buffer store, temperature difference controllers should therefore be installed to limit the maximum temperature via the measuring sensor (= lower storage sensor). The maximum temperature can be set for example to 30°C.

If the domestic water storage cools down as a result of more water being drawn off, then charging continues if a useful temperature level exists in the buffer tank.

To avoid undesirable heating up of the colder buffer tank during the charging operation, an additional three-way valve can be installed in the return line of the discharge circuit. If a higher temperature is then measured at the temperature sensor than in the colder buffer, then the three-way valve switches over the flow to the warmer buffer tank.

The three-way valve is not necessary for buffers with stratified charging equipment, as the buffer discharge return line is led into the respectively matched temperature level through the stratified charging equipment.

5.4 Heat exchangers

5.4.1 Design types

5.4.1.1 IMMERSED HEAT EXCHANGERS

Stores with immersed heat exchangers are most often installed in solar systems for one- and two-family homes. These internal heat exchangers are wound with (Cu-) plain, finned tube or plain steel or stainless steel tube. For their design, and for a logarithmic mean temperature difference of 10 K (see also the following pages), the following approximate formulae are valid:

- plain tube heat exchangers: 0.2 m² area per m² of collector field
- finned tube heat exchangers: 0.3–0.4 m² area per m² of collector field.

In the case of plain tube heat exchangers the energy is transmitted via the surface of the tube. As the temperatures of the entire surface of the tube and that of the medium inside the tube are very close, the same temperature difference between the medium in the tube and the surrounding medium is available over the whole surface. On the other hand the average temperature difference between the surface of a finned tube heat exchanger and the surrounding medium is lower than that for plain tube heat exchangers because of the lower temperature at the ends of the fins (see Figure 5.11).

One square metre of surface on the plain tube heat exchanger can therefore transmit more energy than one square metre of the surface of a finned tube heat exchanger. The surface area of a finned tube heat exchanger is, however, significantly increased by the fins, so that a finned tube heat exchanger – in spite of a lower transmission performance per square metre – is more compact than a plain tube heat exchanger with the same performance.

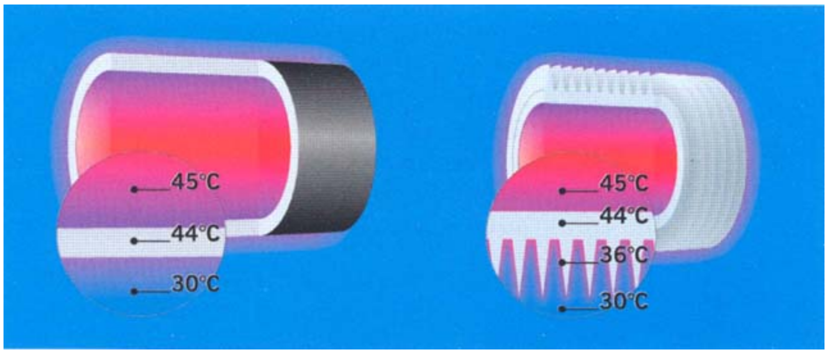


Figure 5.11. Temperature progressions in plain and finned tube heat exchangers

In large solar energy systems, immersed heat exchangers take up a significant volume in order to increase the efficiency of the collector field, especially if the logarithmic mean temperature difference is to be limited to 5 K. If several stores are used, then one heat exchanger with the full transmission performance is required for each store, which leads to higher costs. In larger solar systems, therefore, external heat exchangers are usually installed so that all stores can be charged with just one heat exchanger. Even if a further pump is required for these systems, this variant is preferable.

5.4.1.2 EXTERNAL HEAT EXCHANGERS

For external heat exchangers we similarly differentiate between tubular and flat plate heat exchangers. Tubular heat exchangers made from stainless steel are mainly used in solar energy systems for heating the water in swimming pools.

In the case of flat plate heat exchangers (Figure 5.12) we can differentiate between screwed and soldered models. In the *soldered* version, pressed stainless steel plates are soldered together. In the *screwed* version, the stainless steel plates are fitted with seals and then screwed together with threaded rods. Soldered plate heat exchangers can normally be obtained up to particular performance sizes, and in the smaller performance area are cheaper than the screwed variants. For the solar energy systems considered in this chapter, soldered plate heat exchangers using the counter-current principle are preferred.

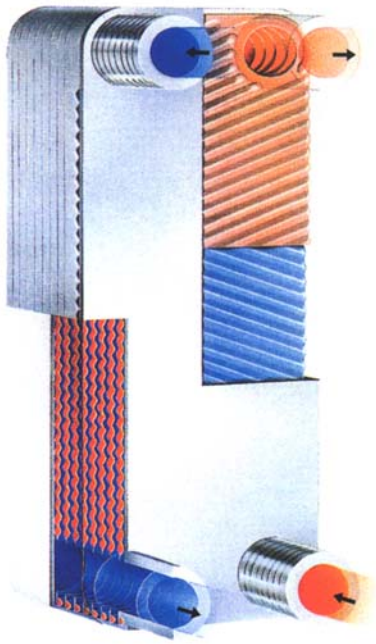


Figure 5.12
Cross-section through a plate heat exchanger (SWEP, Hildesheim)

To avoid corrosion damage, soldered plate heat exchangers should not be used for heating swimming pool water.

Heat exchangers differ from one another on the basis of the plate geometry, the once-through-flow and the construction. A heat exchanger can therefore not be replaced by another model from the same or another manufacturer without a recalculation.

5.4.1.3 COMPARISON OF IMMERSED AND EXTERNAL HEAT EXCHANGERS

Advantages of immersed heat exchangers:

- Simple system construction with few components.
- Without domestic water being drawn off, mixing takes place only by convection in the individual tanks.

Disadvantages of immersed heat exchangers:

- With several stores, a heat exchanger dimensioned for the full performance of the collector field is required for each tank: this leads to high costs.
- Highly stratified charging systems can be used only with special heat exchangers.

Advantages of external heat exchangers:

- With several stores, costs are lower than for immersed heat exchangers.
- Stratified charging systems are simpler to implement.

Disadvantages of external heat exchangers:

- Additional components; complicated installation on site.
- In the event of an unfavourable arrangement of the inflow on the charging side, disturbance to the temperature stratified effect in the tanks.

5.4.2 Collector circuit heat exchangers

See Figure 5.13. Collector circuit heat exchangers are designed for a maximum performance of 600 W/m² of collector field.

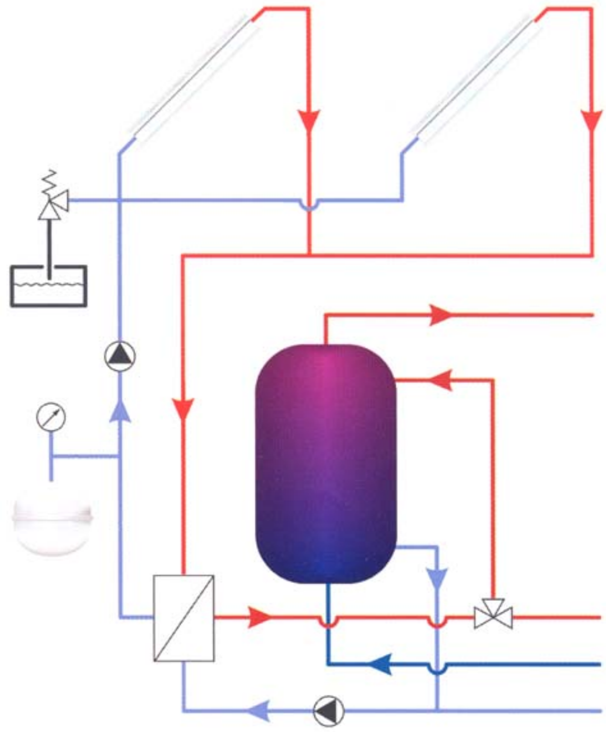


Figure 5.13. External collector circuit heat exchanger

The figure 600 W/m² is a guide value that arises from averaged values for the irradiated power of the sun and the efficiency of the collectors. The assumptions for this are an irradiance of 1000 W/m² of collector field and an assumed efficiency of 0.6.

Through the dynamics of the irradiated power and the operating conditions in the collector circuit, this value is rarely achieved. On the other hand, the value of 600 W/m² of collector field can indeed be exceeded briefly. For these cases the temporary under-dimensioning of the heat exchanger and the resulting increase of the temperature level in the collector circuit are acceptable, in order to keep the heat exchanger costs within a sensible range.

The temperature spread of the collector circuit (inlet/outlet of heat exchanger) is obtained from the following formula:

$$\Delta\theta = \frac{\dot{Q}_{col}}{\dot{m} c_{G,W}}$$

where $\dot{Q}_{col}$ is the collector performance (W), $\dot{m}$ is the mass flow (kg/h), and $c_{G,W}$ is the specific heat capacity of the solar fluid (Wh/kgK).

Collector systems have different temperatures at different times of the day depending upon the solar radiation and the charging condition of the store. For dimensioning the heat exchanger, the temperature at the start of storage charging is used. At the outlet of the heat exchanger (collector circuit return line) a temperature of 5–10 K above the cold water temperature is used for systems with buffer stores; for systems with domestic water stores a temperature of 0–5 K above the cold water temperature is used. These temperature differences occur because a buffer circuit that is connected between the collector circuit and the domestic water system is at a higher temperature than the cold water temperature because of the necessary temperature difference for heat transfer. The collector circuit has a higher temperature than the tank temperature owing to the necessary additional heat transfer.

For central Europe, with an average cold water temperature of 12°C, this would amount to temperatures of 22°C and 17°C respectively. In the example in section 5.4.3, the temperature pairs are used for systems with buffer storage tanks. In warm climates the cold water temperature may be higher – up to 25°C or more.

The inlet temperature into the heat exchanger is derived by adding the outlet temperature in the primary solar circuit and the temperature spread arising (see formula above). On the secondary side of the heat exchanger the temperature spread θ_A–θ_E is equal to the temperature spread θ_A–θ_E on the primary side, where θ_A = exit temperature and θ_E = entry temperature. At the entry to the secondary circuit (buffer charging circuit) the temperature is 17°C. The volumetric flow on the secondary side is obtained from the calculation of the heat exchanger.

Note: Because of the different designs of heat exchangers every manufacturer achieves different values for flat plate heat exchangers with the same exchange surfaces. Therefore the heat exchangers used must be calculated with a program from the respective supplier.

5.4.3 Buffer tank discharge circuit heat exchangers

For systems that, apart from the collector circuit heat exchanger, require an additional heat exchanger to transfer the heat to the domestic water circuit, the following considerations are necessary:

- To avoid limescale build-up, a constant entry temperature should be set before the inlet to the heat exchanger by means of a thermostatically controlled three-way mixing valve (see Figure 5.14). This should be between 55°C and 60°C or, for designs with auxiliary heating in the buffer tank, between 65°C and 70°C.
- In selecting the heat exchanger it is necessary to consider the possibility of subsequent cleaning, bearing in mind particularly the lime content of the water. Considering the better cleaning possibilities and the avoidance of a type of crevice corrosion in the heat exchanger soldering, screw-fitted heat exchangers are recommended here. These can be reactivated by (cost-intensive) dismantling and cleaning if the flushing/cleaning processes are ineffective. However, for lower performance levels, the much higher price compared with that of soldered heat exchangers makes their use undesirable.

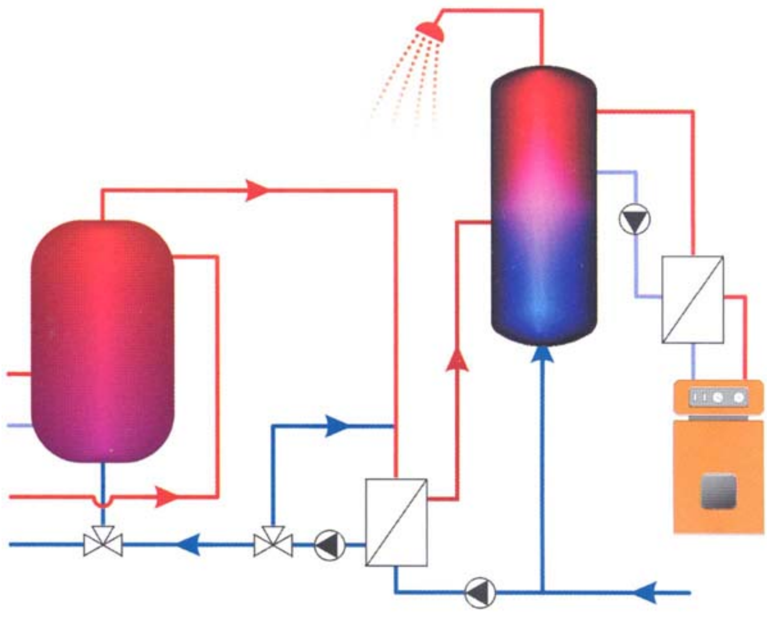


Figure 5.14. Heat exchanger using the storage charging principle

Next Page

5.4.3.1 STORAGE CHARGING PRINCIPLE WITH AUXILIARY HEATING IN THE STANDBY STORAGE

The following pairs of temperatures can be used for the basis of the design of the buffer discharge circuit heat exchanger (using the same example as before):

- Buffer tank circuit side:
  Inlet: 55°C
  Outlet: 17°C
- Domestic water side:
  Inlet: 12°C
  Outlet: 45°C

Owing to a large temperature spread in the discharge circuit of the buffer store, the highest possible cooling of the buffer is achieved – even with charge conditions at high temperature levels. This temperature spread is established on the basis of practical experience in which the domestic water entry temperature is preset by the domestic water mains. The volumetric flows for the calculation of the heat exchanger are obtained from the thermal energy to be transferred. The energy to be transferred by this store-charging system is designed according to the water consumption profile and the collector field efficiency.

In the same way as for solar stores in one- and two-family homes, the domestic water store (in the case where the store is charged through a buffer circuit) should be charged in the lower area if possible, which means it then has a dedicated solar storage area. This is then, apart from regular thermal disinfection by a boiler, only charged by solar heat from the buffer circuit. Auxiliary heating by the hot water boiler is then carried out only for the upper standby section of the domestic water tank.

In the following section, the heat exchangers for charging the solar area in the domestic water store are calculated.

5.4.3.2 ONCE-THROUGH-FLOW PRINCIPLE

With the once-through-flow principle, the heat exchanger (Figure 5.15) is matched to the maximum domestic water consumption peak so as to be able to discharge the buffer circuit at the moment of highest consumption. This is an essential precondition, as otherwise the heat in the buffer is not transferred sufficiently at the peaks and the tank can only be discharged partially. If only a small part of the overall consumption is withdrawn at peak times, the heat exchanger can be designed for example to 50% of the calculated or measured withdrawal peak.

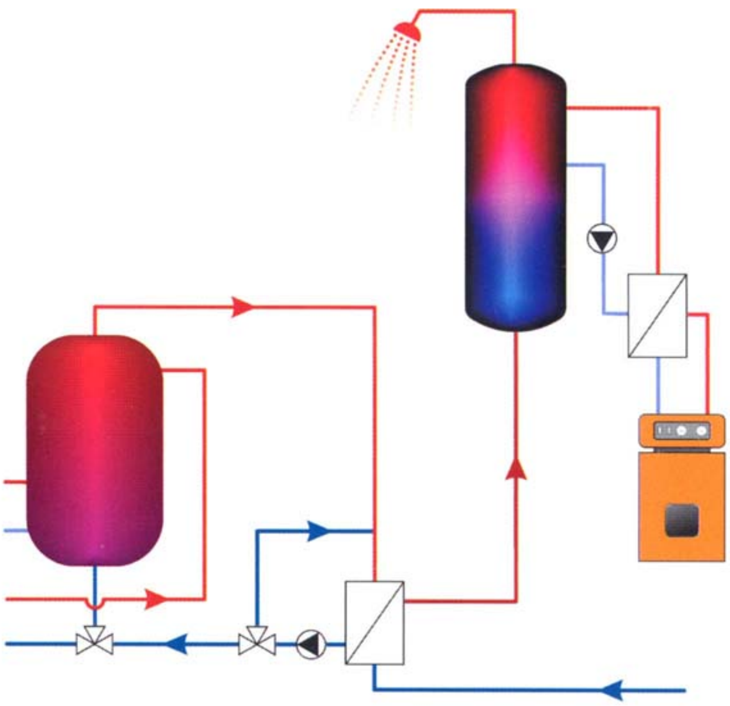


Figure 5.15.
Heat exchanger using once-through-flow principle

6 Solar concentrating systems

The temperature level that can be achieved with non-concentrating solar thermal collectors is limited. At the most a level of approximately 200°C can be reached with high-end vacuum tube collectors. A further increase of temperatures beyond this level is technically hardly achievable. In addition, above 100°C the collector efficiency decreases significantly. However, looking at the required temperature levels in the market segments of process heat or electricity generation by thermal processes, far higher temperatures are needed. Such temperatures can only be generated by the concentration of sunlight.

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.

The theoretical upper value of concentration is 46,211; it is limited by the fact that the sun is not a point source of radiation. By concentrating solar radiation a maximum temperature of 5500°C – the temperature of the sun's surface – can be achieved. However, in practice these maximum values have never been reached, and in general they are not needed in any case. With a rising concentration ratio, the theoretical temperature limit also increases. In practical applications, operating temperatures commonly do not even come close to the theoretically possible temperature (see Table 6.1). There are two main reasons for this: first, it is not possible to manufacture or install to the ideal and, second, heat is carried away, which continuously reduces the temperature. However, if the heat removal is interrupted, the temperature in the absorber can rise dramatically.

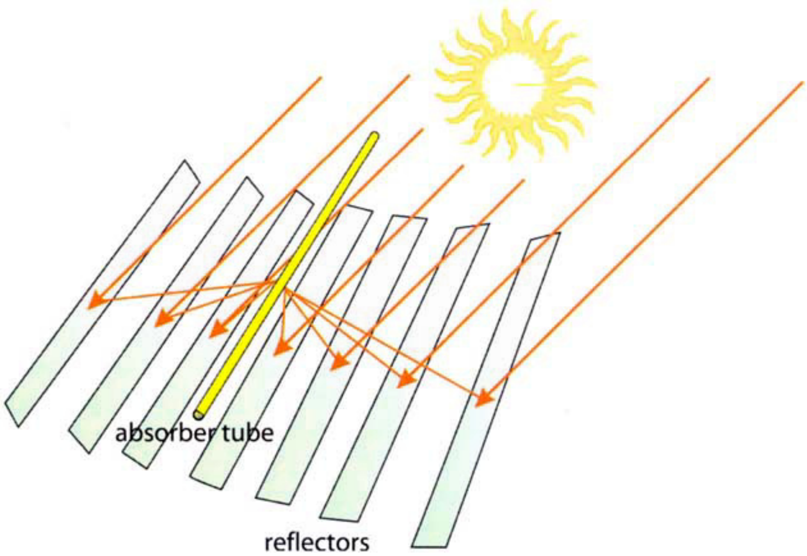


Figure 6.1a. Concentration of solar radiation: reflectors with one-axis tracking

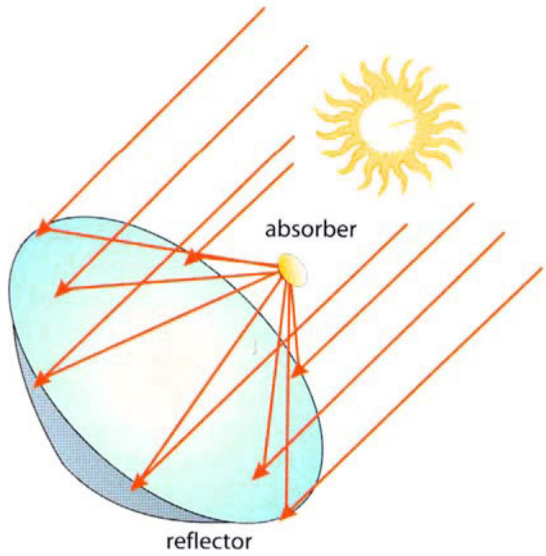


Figure 6.1b.
Concentration of solar radiation: single reflector with two-axis tracking

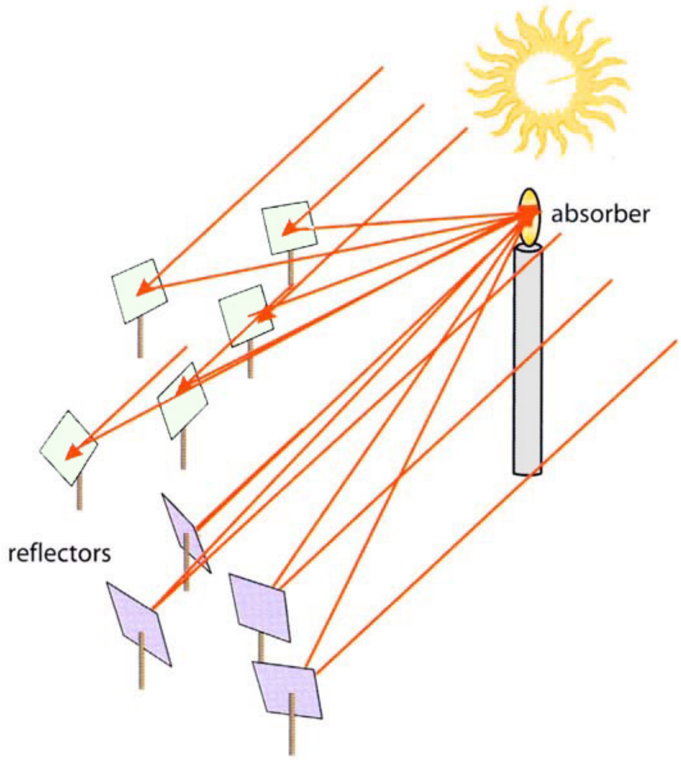


Figure 6.1c.
Concentration of solar radiation: multiple reflectors with two-axis tracking

6.2 Concentrating systems providing process heat

The generation of energy- and cost-efficient heat at temperature levels above 150°C is possible only with solar systems that make use of concentrating collectors, in contrast to non-concentrating systems or collectors with low concentration ratios (such as compound parabolic concentrators). Commonly the demand for process heat is strong in the temperature ranges 80–250°C and from 900–1500°C. Of particular interest is the market segment for low-temperature process heat from 80–250°C. Applications operating in this temperature range have used approximately 300 million MWh annually in the EU (8% of the end energy demand). The chemical industry, the pulp and paper and textile industry and the food processing industry consume large parts of this heat. The areas of application are numerous and include not only such widely varying processes as the heating of baths (for example for electroplating or cleaning),

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

drying, chemical processes (thermal separation, for example), melting or boiling, but also the generation of low-temperature process steam and the supply of heat to drive absorption refrigeration systems (solar cooling).

A selection of concentrating collectors was presented in section 6.1. With regard to the economic aspects of the provision of process heat, *parabolic trough collectors* are of particular interest. These concentrate the incident direct solar radiation linearly by means of parabolic curved reflectors onto a black-coated absorber tube. The aperture span of these collectors usually ranges between 2 and 4 m. The absorber tube takes up the solar radiation and converts it to heat, which it transfers to the heat transfer fluid that flows in the tube. Commonly used heat transfer fluids are water (hot water or steam), air and also thermal oils. Generally the latter re-transfer the heat to water or air in a heat exchanger at a further stage of the line.

Compared with glazed flat-plate collectors, these systems exhibit fewer heat losses. Among other aspects, this results from the small absorber surface area compared with the aperture (solar radiation collection area) and the selective coating of the absorber tube, which reduces the emittance of infrared radiation and thus radiation losses. In addition, a glass envelope that sits around the absorber tube reduces convective losses. In order to achieve even higher collector efficiencies, and thus make it possible to reach higher operating temperatures, the space between the glass envelope and the absorber tube is evacuated.

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.

A further significant difference between tracked concentrating collector systems and the conventional solar thermal systems such as glazed flat-plate collectors or evacuated tube collectors is shown in the operation and safety concepts.

In conventional collector systems, if a standstill occurs (for example if no heat is removed, or if a component fails) then in order to prevent stagnation temperatures being exceeded, various substantive measures (such as expansion vessels) have to be incorporated. In contrast, tracked collectors make use of safety control routines that defocus the collector to avoid exceeding stagnation temperatures. However, suitable safety devices, such as a flow indicator, are needed to ensure the flow of heat transfer fluid through the absorber, and thus the removal of heat, before the collector is focused, in order to avoid overheating of the system.

Some evacuated tube collectors integrate compound parabolic concentrators (CPCs) into the glass envelope (see Figure 6.2) in order to enhance the aperture. Also simple flat absorber stripes are used for that purpose.

Figure 6.3 shows the efficiency of various collector types by plotting the annual energy yield per square metre of collector surface area against the mean flow temperature. Whereas the energy yield for non-concentrating collectors decreases significantly with increasing flow temperature up to a maximum temperature of 100°C, the decrease is considerably less for evacuated tube collectors with CPCs and parabolic trough collectors. The common non-tracking glazed flat-plate collectors and evacuated tube collectors use the entire solar radiation (that is, the direct irradiation and the diffuse sky irradiation), in contrast to concentrating solar systems, which use

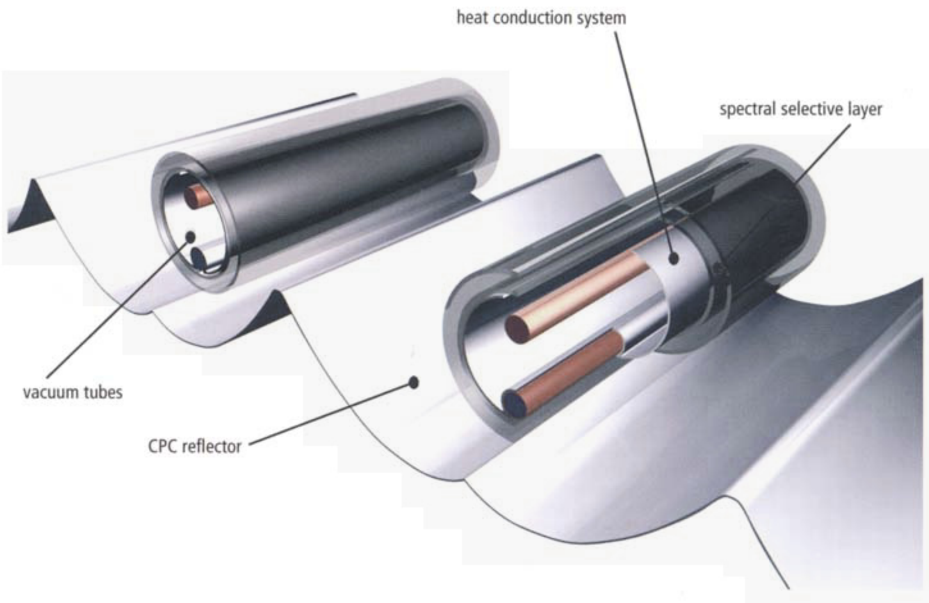


Figure 6.2. Schematic structure of a CPC tube collector. Source: Consolar

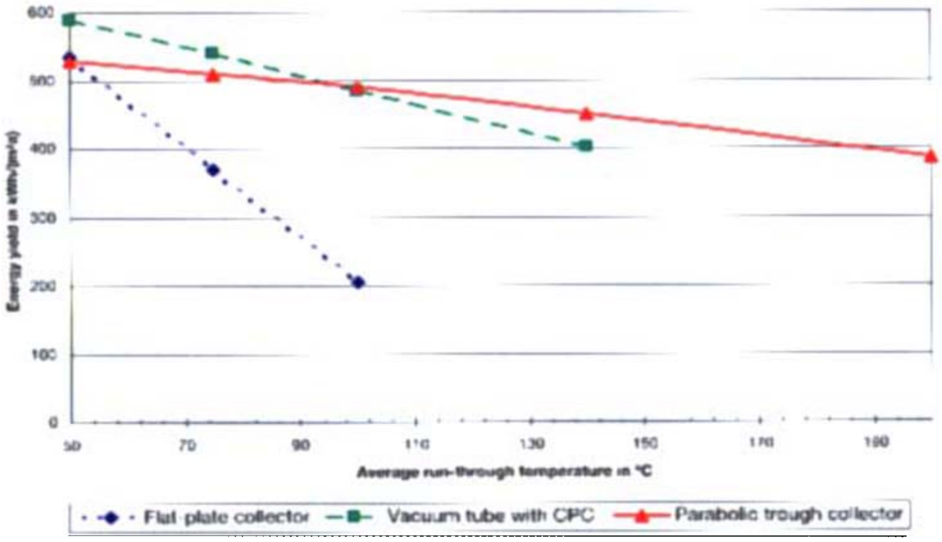


Figure 6.3. Energy yield against mean flow temperature for various collector types at Würzburg, Germany. Source: Klaus Hennecke

only the direct irradiation. The energy yield in Figure 6.3 was calculated for southerly oriented collectors with an inclination angle of 40°, located in the city of Würzburg, Germany.

The energy yield of a collector system depends not only on the construction of the collector but also on the annual amount of direct irradiation. Würzburg receives a mean annual direct irradiation of 1066 kWh/m^{2}a. Comparison of parabolic trough collectors of simple construction with conventional solar thermal collectors shows that, even in a mid-European climate, the parabolic trough collector has a number of advantages, in particular when higher operating temperatures are needed. At southern European locations with a higher share of direct irradiation the advantages become even larger.

The system integration of concentrating collectors to provide process heat does not differ much from conventional systems that supply process heat. The centrepiece of the system is the collector field: that is, arrangement of the collectors on the ground or on the roof of a building. The heat transfer fluid (HTF) circulates through the field. By measuring the temperature of the HTF at the outlet of the collector, a controller regulates the flow rate in harmony with the irradiance. The gained heat is then transferred to a heat exchanger, where it is either used directly in a process (for example to heat a bath or to preheat feed water or combustion air; see Figure 6.4) or stored in a short- or long-term heat store.

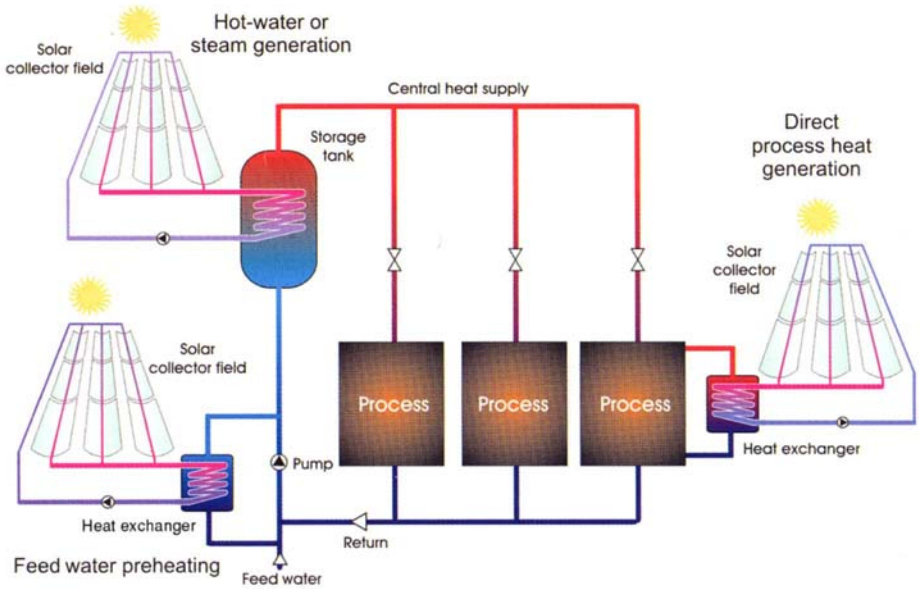


Figure 6.4. Schematic of various options for integrating solar systems into a conventional heat supply. Source: DLR

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.

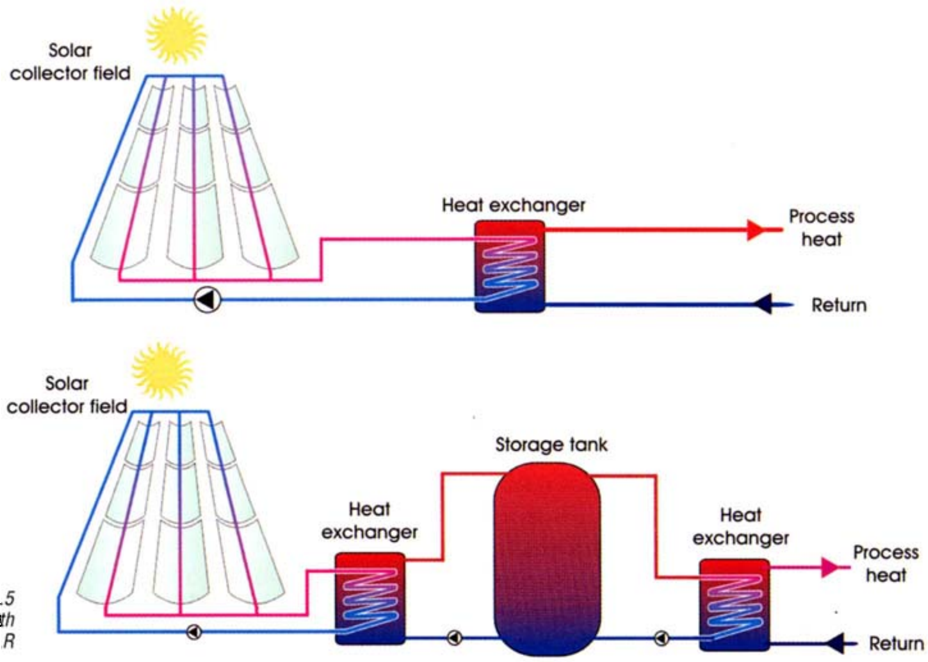


Figure 6.5 Solar system without (above) and with storage (below). Source: DLR

More common are processes that are operated for only 5–6 days a week, or processes with frequent interruptions. Such situations require the use of a store for any excess heat. The required heat can then be supplied to the user whenever it is needed. In this case the dimensioning of the store and the collector field depends not only on the required heat demand, temperature level and system design, but also on the desired heat capacity of the storage, and thus the amount of time for which heat can be supplied. In general a distinction is made between: short-term storage with a capacity of a number of hours, which covers daily fluctuations; storage systems with a capacity for several days; and seasonal storages. The store has to be dimensioned according to the specific demand.

In contrast to solar thermal power plants for electricity production, solar thermal process heat systems should be installed directly at the location where the heat is required in order to avoid losses caused by the need to transport the heat. Hence sufficient space for the collector field and a relatively high annual irradiation need to be available at the specific location.

Typical investment costs for a solar thermal process heat system are given in Table 6.2.

Table 6.2. Investment costs for various collector types (indicative; market prices fluctuate and differ per country)

Collector type	Costs (€/m²)
Flat-plate collector	250-300
Compound parabolic concentrator (CPC)	300-350
Parabolic trough collector	300-400
Evacuated flat-plate collector	400-600
Evacuated tube collector	400-600
Evacuated tube collector with CPC	400-600

The maintenance costs (cleaning etc.) for conventional collectors are of the order of €2.5/m^{2}a; for parabolic trough collectors they amount to approximately €5/m^{2}a.

Considering the costs for the total system and the single components, about 80% of the investment cost relates to the collector field (for field sizes of >1000 m^2), including the erection, support structure and piping. The remaining 20% relates to the heat exchangers, pumps, control system and planning. Whereas the integration of short-term storage does not influence the investment costs significantly, long-term storage tanks can be far more costly, reaching shares of 10–20% of the total investment cost.

The total investment costs for solar thermal systems for process heat are about €250–1000/$250–1000/£165–600 per kW$_{th}$ (kilowatt–thermal) of installed capacity. Accordingly the resulting energy costs are about €0.02–0.05/$0.02–0.05/£0.014–0.035 per kWh$_{th}$ for low-temperature heat supply, and €0.05–0.15/$0.05–0.15/£0.035–0.10 per kWh$_{th}$ for mid-temperature heat.

For the near future it is important to demonstrate the integration and reliability of solar thermal process heat systems in suitable applications. One obstacle for such systems is the availability of space to erect the collector field. Higher specific costs compared with those of conventional process heat systems are another barrier. However, cost reduction potentials are seen in modifications of the collector designs, and in smaller, modular collector units that are suitable for erecting on a rooftop or for roof integration. Further potential is expected from increasing automated operation, thus reducing the operation and maintenance (O&M) costs. Mass production, the reduction of O&M costs and the improvement of system design and collector efficiencies are expected to cut costs by half by the year 2010.

Until now the European market did not offer concentrating systems for process heat applications. However, several current European projects are aimed at the development of commercial collectors, and some companies in Israel and the USA already offer commercial systems. Also, a number of systems are operating in the USA, with collector field sizes ranging from 200 to 3000 m^2.

In addition, with the 'Campaign for Take-Off' the European Commission is pursuing the aim of having 2,000,000 m^2 of solar thermal collectors installed for industrial process heating and solar cooling. By reaching this goal, it is expected to realize a saving of prime energy of about 2 million MWh/a. In 2001 solar thermal collectors with a total area of 10,000 m^2 were operating in the field of industrial process heat in Europe. In the near and mid-term future, concentrating collectors could play an important and growing role in the spreading of supplying solar process heat.

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. In particular solar thermal power plants, apart from photovoltaics, 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.

6.3.1 Parabolic trough plants

The first solar thermal power plants were developed in the USA in 1906. The first demonstration plants were erected and successfully tested in the USA and near Cairo, Egypt, still a British colony at that time. Amazingly, these systems looked almost like the systems of today. However, problems with materials and other technical difficulties put an end to the first attempts at large-scale solar electricity generation in 1914, shortly before the outbreak of the First World War.

In 1968 the USA laid the basis for the renaissance of solar thermal electric technology. The US public electric utilities were obliged by the power of the Public Utilities Regulatory Policy Act to buy electricity from independent power producers at a clearly defined tariff. After a doubling of the electricity costs in only a few years owing to the oil crisis, the Californian electric utility Southern California Edison (SCE) offered long-term conditions for the feed-in of electricity from renewable energy systems. In combination with tax incentives such as an exemption from paying property tax for solar power plants, the development of solar thermal power plant projects started to become financially interesting. In 1969 the company LUZ was founded, which concluded a feed-in contract for solar thermal electricity over a period of 30 years with SCE in 1983. The first commercially operated solar thermal power plant with parabolic trough technology was erected in 1984. From then on new solar thermal power plants with increased size and improved technology followed each year (see Table 6.3). In the mid 1980s electricity prices went down again. After the abolition of tax exemptions at the end of 1990, LUZ went bankrupt just before starting the erection of its tenth solar thermal power plant.

Table 6.3. Characteristics of different parabolic trough collectors

Collector type	LS-1	LS-2	LS-3	EuroTrough
Year of first installation	1984	1986	1988	2001
Concentration ratio	61	61	82	82
Aperture width (m)	2.5	5.0	5.66	5.66
Collector length (m)	50	48	99	150
Aperture (m^2)	128	235	545	825
Absorber tube diameter (mm)	42.4	70	70	70

Although electricity generation from solar thermal power plants is significantly cheaper than from photovoltaic systems, no further commercial solar thermal power plants have been built since 1991. However, a number of new solar thermal power plant projects are currently being developed. The World Bank has allocated US$200 million for financial support of the erection of combined solar thermal and natural-gas-fired power plants in developing countries such as Egypt, Mexico, India and Morocco. A higher feed-in tariff for electricity from solar thermal power plants is being paid in Spain, and other southern European countries are preparing similar support measures.

Up to now solar thermal power plants with parabolic trough technology have been the only commercially operating plants. After the oil crisis nine parabolic trough plants were erected from 1984 to 1991 in the Mojave Desert in California on a surface area of more than 6 km^2. They are called *SEGS plants* (solar electric generation systems) (see Figure 6.6 and Table 6.4). More than a million mirror elements with a total aperture of

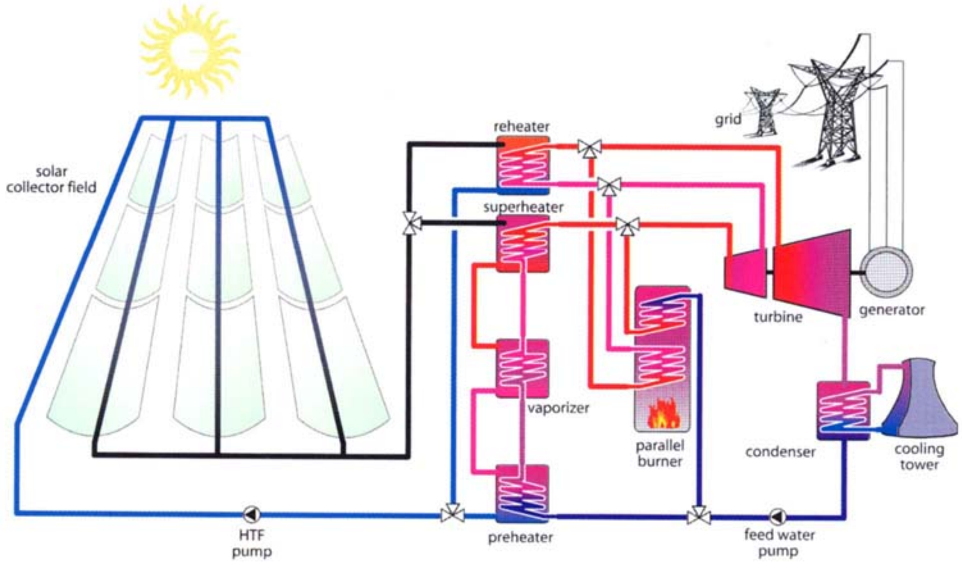


Figure 6.6.
Schematic of an SEGS plant

Table 6.4.
Technical data for parabolic trough-based SEGS plants in California

Plant	I	II	III	IV	V	VI	VII	VIII	IX
Year of commissioning	1984	1985	1986	1986	1986	1988	1988	1989	1990
Net capacity (MW)	13.8	30	30	30	30	30	30	80	80
Land use (1000 m^2)	290	660	800	800	860	660	680	1620	1690
Aperture (1000 m^2)	83	165	233	233	251	188	194	464	484
HTF outlet temp. (°C)	306	321	349	349	349	391	391	391	391
Efficiency (%)									
– Steam turbine (solar)	31.5	29.4	30.6	30.6	30.6	36.6	36.6	36.6	36.6
– Steam turbine (gas)	–	36.3	36.3	36.3	36.3	39.5	39.5	36.6	36.6
– Solar field (thermal)[a]	35	43	43	43	43	43	43	53	50
– Solar-to-electric (net)[a]	9.3	10.6	10.2	10.2	10.2	12.4	12.3	14.0	13.6
Specific invest. costs (US$/kW)	4490	3200	3600	3630	4130	3860	3860	2890	3440

[a] Design

2,300,000 m^2 focus the sunlight in these plants, which have an electrical capacity of 354 MW. Each year the SEGS plants generate about 800 million kWh of electricity, enough to cover the demand of 60,000 Americans. Eight of the SEGS plants can also be operated with fossil fuels, so that electricity can be supplied during night-time or periods of bad weather. However, the annual share of fossil fuel, in this case natural gas, is limited by law to 25% of the entire annual thermal input. The total investment for the SEGS plants amount to more than US$1.2 billion. Up to now these plants have supplied more than 10 billion kWh of electricity to the grid. The levelized electricity costs have decreased from system to system, with US$0.26/kWh for the first SEGS plant down to US$0.12–0.14/kWh for the plants that were erected last.

The principle of operation of the parabolic trough plants is easy to understand. Large reflectors, arranged in the form of a trough-shaped collector, focus the sunlight onto a focal line. Several collectors are joined together in rows of 300–600 m (Figure 6.7). Again, a number of parallel rows then form the entire solar field.

Each single collector can be turned around its longitudinal axis to track the sun. The sunlight is concentrated up to 80 times onto an absorber tube that is located in the centre of the focal line. A glass envelope is placed around the absorber tube in order to reduce heat losses. Heat radiation losses are minimised by applying a special high-temperature-resistant selective coating to the absorber tube. In the Californian plants a specific thermal oil flows through the absorber tubes and is heated to temperatures of up to 400°C.

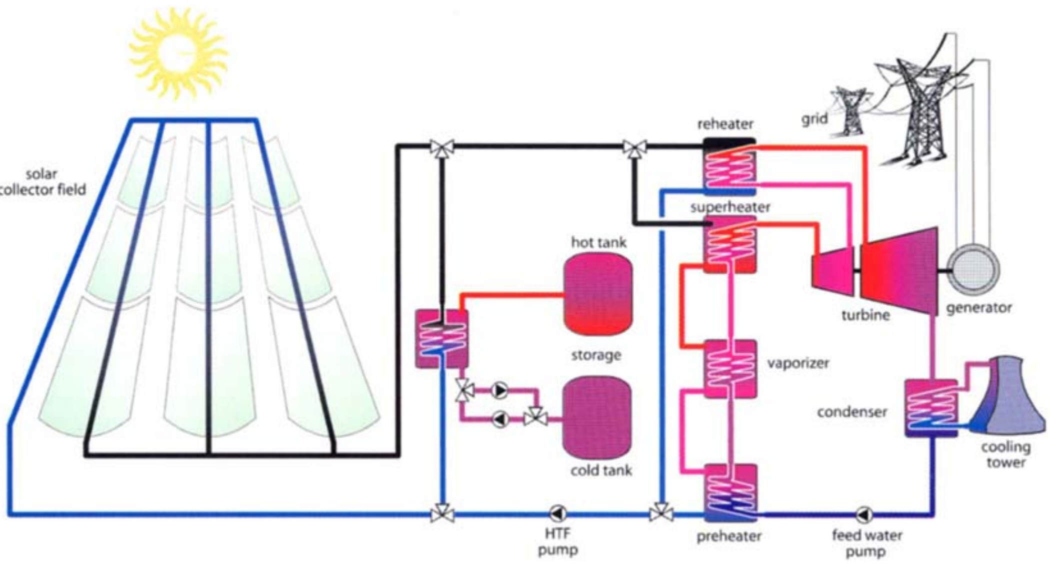
A parabolic trough collector can also be designed according to the Fresnel principle, as shown in Figure 6.8. A prototype that applies this principle has been erected in Belgium. Heat exchangers transfer the solar heat from the heat transfer fluid (HTF) to a water/steam cycle. The feed water is first brought up to higher pressure

Figure 6.7.
Parabolic trough power plants in California. Source: KJC

Figure 6.8.
Parabolic trough collectors. Source: Volker Quaschning

before it is preheated, evaporated and superheated by the HTF. The superheated steam drives a conventional steam turbine generator set to generate electricity. In two-stage turbines with high- and low-pressure stages the steam is reheated between the two stages. Once leaving the turbine the steam is expanded and is then condensed to water before reaching the feed water pump again. In cases of bad weather or at night-time the steam cycle can also be operated with a parallel fossil-fuel-driven boiler.

In contrast to photovoltaic systems a solar thermal power plant can guarantee a daily security of supply. This aspect increases the attractiveness of solar thermal power technology in a power plant portfolio. A useful supply of electricity can either be realized by hybrid operation with fossil fuels or, if solar only, CO_2-emission-free operation is desired, by using thermal storage (Figure 6.9). A well-proven principle in storing high temperature heat makes use of two-tank storage with, for example,



Schematic of a parabolic t
plant with thermal storage

molten salt as heat carrier. In the case of excess solar heat this is transferred via a heat exchanger to the molten salt, which is pumped from a warm to a hot store. In periods with less solar radiation the hot molten salt can be pumped back to the warm tank, heating up the HTF, which then drives the steam cycle.

The parallel steam generator (boiler) can also be fuelled by biomass or hydrogen (produced from renewable electricity). This is another option for generating electricity without emitting additional CO_2.

Current technological developments aim at further improvement of the efficiency and thus reduction of costs. For example, in Southern Spain close to the city of Almería the direct generation of solar steam is being demonstrated (Figure 6.10). Here the parabolic trough collectors directly heat and evaporate water under high-pressure conditions to a temperature of 400°C. Steam at such conditions can directly drive a steam turbine, so that such plants could dispense with the HTF and the heat exchangers.

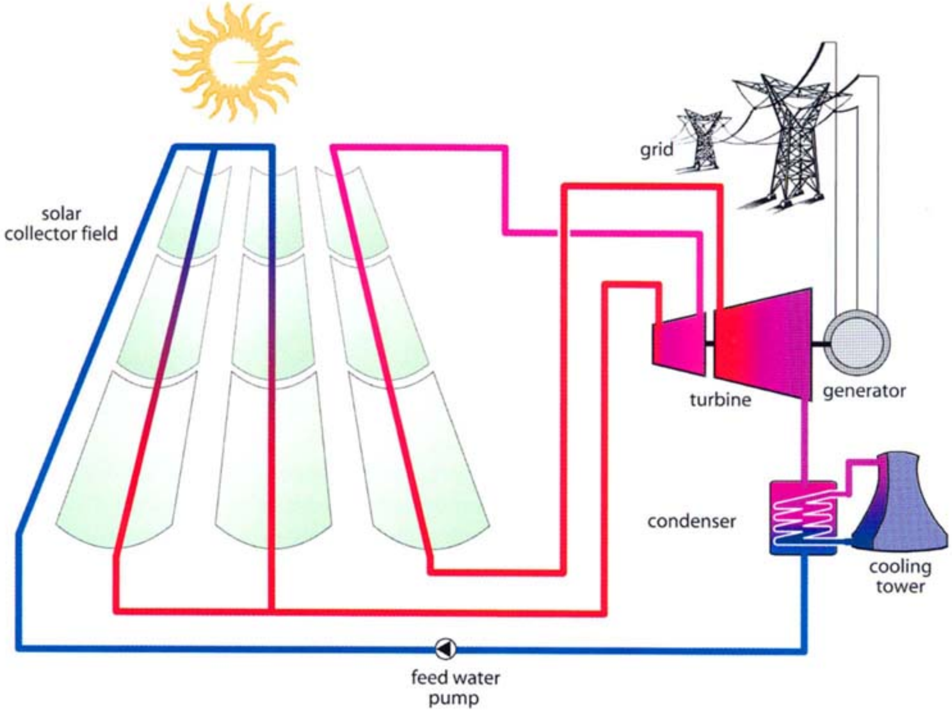


Figure 6.10. Schematic of a parabolic trough plant with solar thermal direct steam generation

The largest potential cost reduction is expected from large-scale production of solar thermal power plants, thus making use of the economies of scale. On a long-term basis cost reductions from €0.15 down to €0.05 per kWh are seen as possible. This would drive costs down to a similar order of magnitude as those of conventional fossil-fuelled power plants, but without the emission of harmful greenhouse gases.

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.

An absorber is positioned at the focal point. The concentrated sunlight heats up the absorber to temperatures of more than 1000°C. Air or molten salt transfers the heat to the power cycle – a gas or steam turbine cycle – where the heat is then converted into electricity.

In contrast to parabolic trough technology, no commercial tower plants are in operation, so far. In Almería (Spain), Barstow (USA) and Rehovot (Israel) pilot plants are operated in which system configurations are being optimized and new components are being tested (Figure 6.12). Also in Spain, the first commercial solar tower plants are in an advanced planning stage.

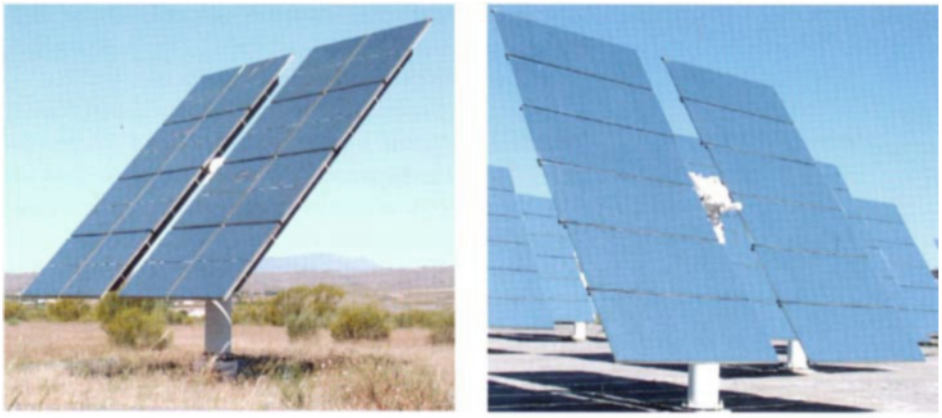


Figure 6.11.
Heliostats. Source: Volker Quaschning

Figure 6.12.
Solar tower test installations in Almería, southern Spain. Source: Stefan Franzen, CIEMAT

The tower concept with open volumetric receivers (Figure 6.13) works as follows. A fan sucks the ambient air into the receiver upon which the heliostats focus the sunlight. Commonly wire mesh, ceramic foam or a metallic or ceramic honeycomb structure is used as the receiver material. This structure is heated by the solar radiation and transfers the heat to the airflow. The ambient air cools the front part of the absorber, whereas very high temperatures arise in the rear part of the absorber material. Thus radiation losses are minimised. The heated air with temperatures between 650°C and 850°C is impelled to a waste heat boiler where water is

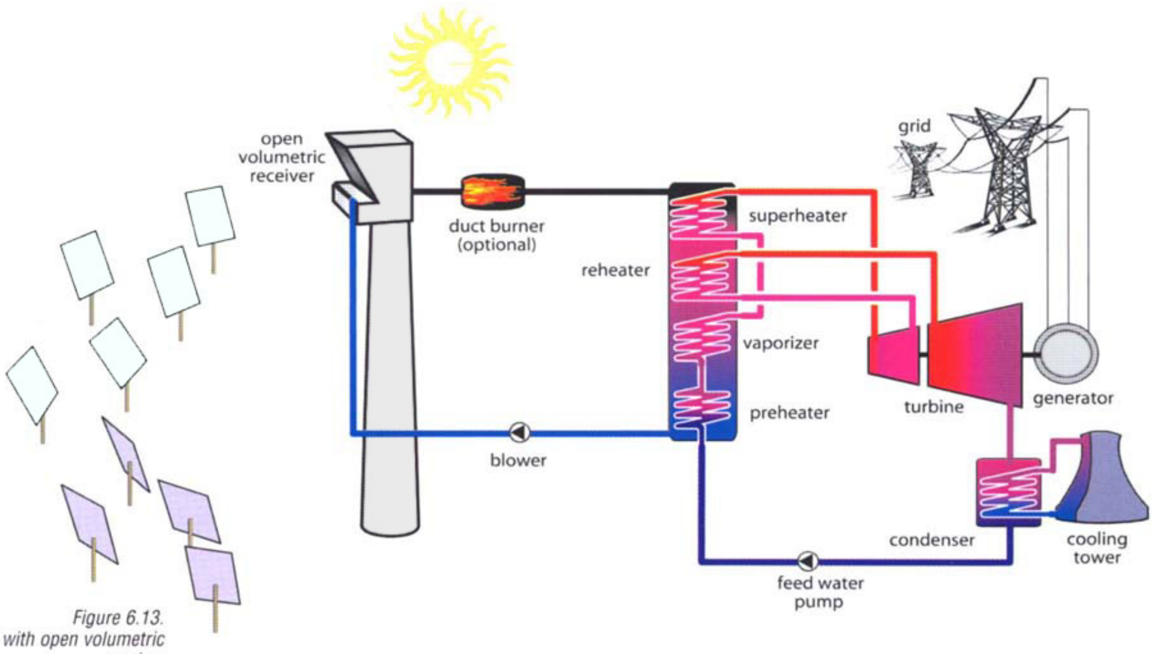


Figure 6.13.
Solar tower plant with open volumetric receiver

evaporated and superheated. Again, the superheated steam drives a steam turbine generator set to produce electricity. This power plant variant can make use of other fuels, for example by means of a duct burner.

Another tower concept that was developed from that just described offers promising options for the mid-term future: the closed volumetric receiver (REFOS concept; Figure 6.14). Here a transparent cupola-shaped silica glass separates the ambient air from the absorber. The air is heated in a pressurised air receiver at a pressure of approximately 15 bar to temperatures of up to 1100°C. With air of this temperature level a gas turbine is driven. Downstream a steam cycle makes use of the waste heat of the gas turbine.

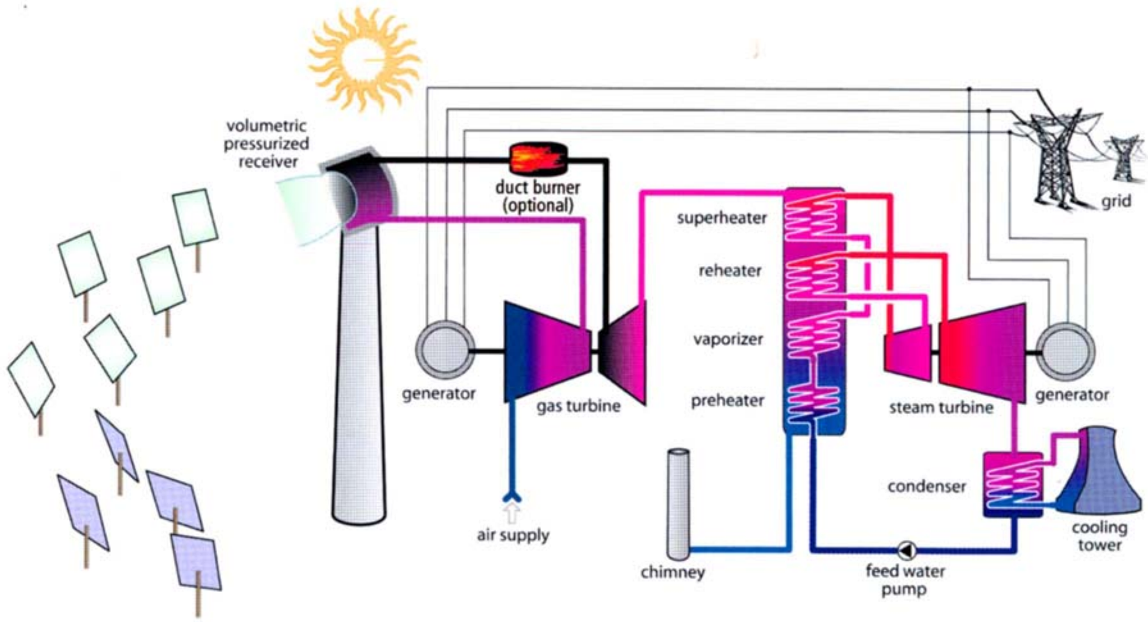


Figure 6.14. Solar tower plant with a pressurised volumetric receiver for solar operation of gas and steam turbines (REFOS)

In general, electrical efficiencies of combined cycles are higher (in the range of 50%) than steam cycle efficiencies (about 35%). The integration of solar thermal energy into combined cycle processes allows solar-to-electric efficiencies of more than 20%. This improvement and its technological prospects justify the increased technological effort and the higher costs of this receiver technology.

The levelized electricity costs are expected to be slightly higher for the first commercial solar tower plants as, in contrast to parabolic trough power plants, there are no series-produced solar tower plants in operation. However, owing to the higher efficiencies that are possible, lower costs are expected in the medium term.

6.3.3 Dish/Stirling systems

Whereas the erection and commercial operation of solar parabolic trough and tower plants is economically viable at electrical capacities of several megawatts, dish/Stirling systems can be also used in smaller units, for example as stand-alone systems to supply remote villages with power.

In these systems a concave mirror in the shape of a large bowl concentrates the solar radiation to a focal point, where the receiver is located. In the receiver the solar radiation is converted into heat and transferred to the heart of the system, the Stirling engine. This engine converts the heat directly into kinetic energy, which drives a generator to produce electricity. In order to direct the solar radiation to the receiver it is necessary to move the concave mirror in two axes, hence tracking the sun.

Solar heat is not the only form of heat that can drive the Stirling engine; heat from any combustion process can also be used. Combinations with a biogas burner can enable the dish/Stirling system to produce electricity also during night-time or at periods of bad weather. The use of biogas in such a system is also entirely CO_2-neutral.

Some prototype dish/Stirling systems have been erected and operated in Saudi Arabia, Spain and the USA (Figure 6.15). The levelized electricity costs are still relatively high in comparison with those of solar tower or parabolic trough plants.

Figure 6.15. Dish/Stirling demonstration systems in Almería, Southern Spain. Source: Volker Quaschning

Table 6.5. Technical characteristics of the EuroDish dish/Stirling system shown in Figure 6.15
Source: Schlaich Bergermann und Partner, Stuttgart

Concentrator diameter: 8.5 m	Reflectivity: 94%
Aperture: 56.6 m²	Working medium: Helium
Focal distance: 4.5 m	Gas pressure: 20–150 bar
Average concentration ratio: 2500	Receiver-gas temperature: 650°C
Electrical gross capacity: 9 kW	Max. operating wind speed: 65 km/h
Electrical net capacity: 8.4 kW	Survival wind speed: 160 km/h

However, a dramatic cost reduction is thought to be possible when such systems are produced in large numbers and in volume production.

6.3.4 Economics and outlook

Concentrating solar systems use only the direct part of the solar radiation, whereas non-concentrating solar systems such as photovoltaic systems also make use of the diffuse part. Tables 6.6 and 6.7 show that the direct normal irradiation increases with decreasing latitude towards the equator more rapidly than the global horizontal radiation.

Table 6.6. Direct normal irradiation and global horizontal irradiation values for various European capitals

	London	Berlin	Paris	Rome	Madrid	Lisbon
Latitude (°N)	51.5	52.5	48.9	41.9	40.5	38.6
Direct normal irradiation (kWh/m²a)	690	686	842	1565	1593	1269
Global horizontal irradiation (kWh/m²a)	956	993	1088	1561	1582	1686

Table 6.7. Values for direct normal irradiation and global irradiation of various regions that are interesting for the installation of solar thermal power plants

	Bari (Italy)	Tabernas (Spain)	Oujda (Morocco)	Cairo (Egypt)	Luxor (Egypt)
Latitude (°N)	41.1	36.1	34.2	30.1	25.4
Direct normal irradiation (kWh/m²a)	1884	2180	2290	2350	2975
Global horizontal irradiation (kWh/m²a)	1659	1832	1995	2093	2438

It is true that solar thermal power plants can also be operated in regions with rather low direct irradiation, but the economic viability decreases significantly there. Suitable regions show an annual total direct normal irradiation in the order of 2000 kWh/m²a or above. In Europe the most suitable regions can be found in southern Spain, southern Italy, Greece and northern Africa.

Today, at good locations, levelized electricity costs of the order of €0.15/kWh can be realized (see Figure 6.16 overleaf). Volume production and technical improvements could lower these costs to below €0.10/kWh. Technically, solar thermal electricity can also be transported from northern Africa to central Europe. Given future transport costs of €0.01–0.02/kWh, a significant part of the electricity supply in central Europe could be covered by environmentally friendly solar thermal electricity in the long-term future.

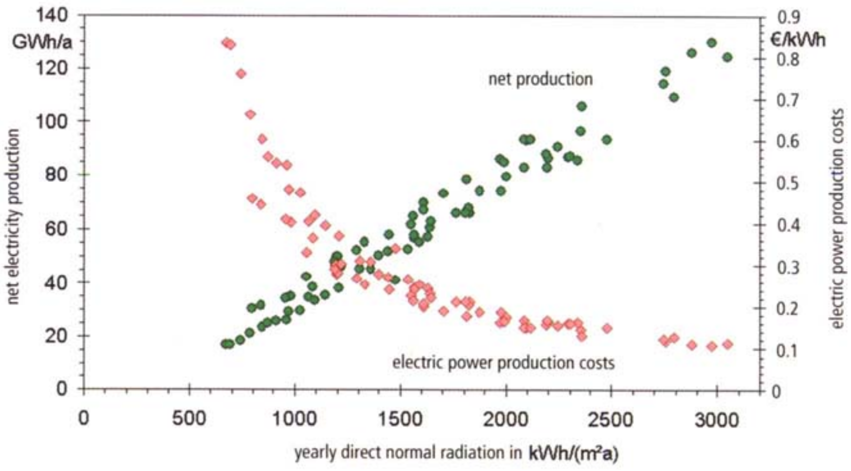


Figure 6.16. Net electricity production and levelized electricity costs of a 50 MW_{el} parabolic trough power plant for 65 different worldwide locations plotted against the annual direct normal irradiation

7 Solar heating of open-air swimming pools

7.1 Introduction

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. 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.

Solar heating for open-air swimming pools has been used for several decades now, and is a well-established technology. However, this does not mean that this application of solar thermal energy has reached its limits yet.

According to statistics in *Sun in Action II*[43], the updated overview of European solar heating markets by the European Solar Trade Industry Federation (ESTIF), about 3000–4000 m^2 of unglazed collectors were erected yearly in the 1990s. The estimated production and sales for 2000 and 2001 were 10,000 m^2 yearly.

If we look at the developments over recent years, heating of the pool is too costly for most swimming pool owners. Existing older conventional heating systems are, however, often replaced either by absorber systems, or the owners do without heating altogether.

If conventional fuels are used for heating pools and spas they are most likely to use natural gas; however, some heat pump pool heaters have emerged in the US markets.

This chapter describes in detail the components, planning, installation and economics of swimming pool absorber systems. The emphasis is on the solar heating of swimming pools (open-air pools in the private area with pool sizes of up to 250 m^2) and public open-air pools (local authority or privately operated). We shall also discuss combination options with systems for domestic water heating and for room heating support. The various options for making use of solar thermal energy in the indoor pool area were described in more detail in Chapter 5.

7.2 Components

7.2.1 Absorbers

Solar open-air pool heating uses absorbers to collect the energy (Figures 7.1 and 7.2). The collector design is characterized by the lack of either a transparent cover and housing or thermal insulation. This simple construction is possible as the systems operate with low-temperature differences between the absorber and the surroundings and with relatively uniform return temperatures (10–18°C).

The swimming pool absorber is generally made from plastic, utilizing a specially stabilized polypropylene polymer as the plastic extrusion. As an alternative, some

Figure 7.1.
Solar absorber in an open-air pool.
Source: Lange GmbH, Telgte

Figure 7.2.
Swimming pool absorber system for a private pool

manufacturers use EPDM extrusion, as it is more flexible and can be fixed directly to roof shingles. Pool absorbers are generally drained in the winter to prevent frost damage to the absorbers and piping.

Because of the risk of corrosion of thermal collectors with copper absorbers, these can be operated in solar systems for swimming pool heating only if a separate solar loop is installed (that is, an indirect system).

7.2.1.1 EFFICIENCY AND YIELD

The use of unglazed and uninsulated absorbers for solar open-air pool water heating has some advantages, owing to the special operating conditions.

In the typical operating range, with a temperature difference, $\Delta\theta$, between the outside temperature and the mean absorber temperature of 0–20 K, absorbers often operate with a higher efficiency than glazed collectors. This is because the optical losses (normally about 10–15% with respect to the amount of solar radiation) through a transparent cover do not arise, and the thermal losses are not so significant because of the low temperature difference. These thermal losses increase with operating temperatures, but this rarely occurs because of the moderate absorber temperatures found under normal operating conditions. The wind speed is the decisive factor that causes losses and hence has a negative effect on the efficiency of the absorber (Figure 7.3).

7.2.1.2 DESIGNS

Apart from a few special designs, plastic absorbers can be subdivided into two groups:

- tube absorbers (small tube absorbers)
- flat absorbers.

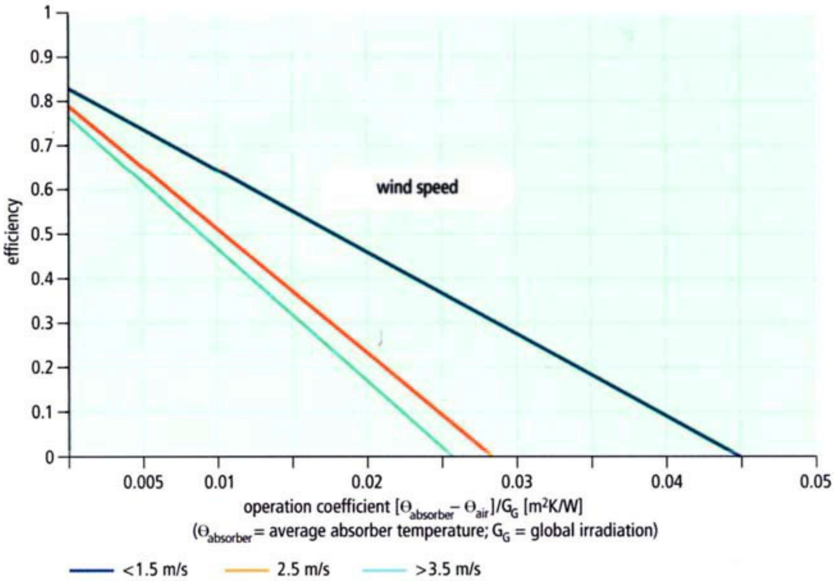


Figure 7.3.
Characteristic curve as a function of wind speed

The *tube absorber* (Figure 7.4) is the simplest design. A number of smooth or ribbed tubes (small tubes) are arranged in parallel and, according to the design, are connected together either with intermediate webs or by retainers at a given spacing. Absorber lengths of up to 100 m can be achieved, and obstructions such as chimneys or rooflights can easily be circumvented.

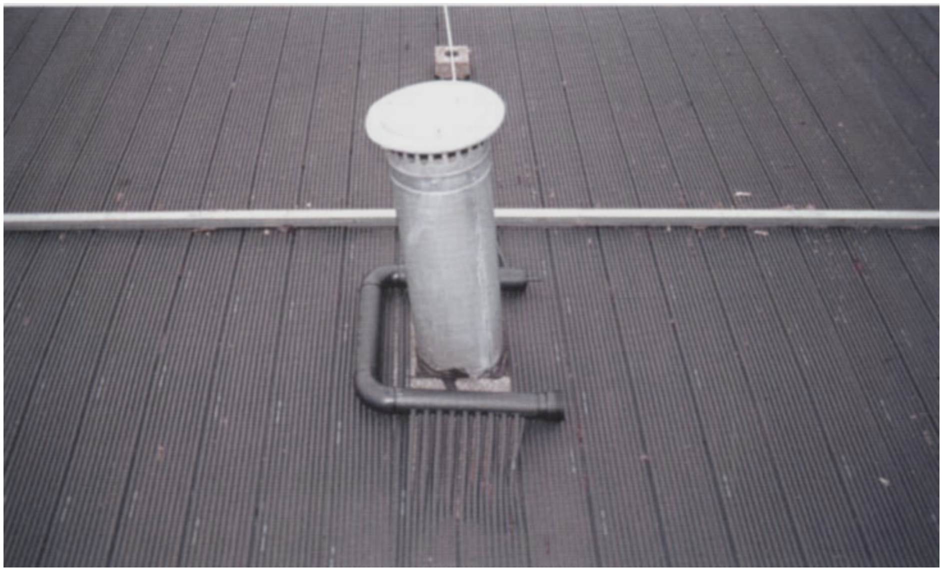


Figure 7.4.
Chimney bypass with an EPDM tube absorber. Source: DGS

In the case of *flat absorbers*, sometimes also called *plate* or *cushion absorbers*, the channels are linked together structurally. This produces plates of different dimensions with a smooth surface. This has the advantage that there are no grooves in which dirt or leaves can accumulate and solidify. The self-cleaning effect during rain is also better.

The influence of the design form on the conversion factor with different inclination angles can be measured, but it is minimal. Variations of the angle of incidence lead to small differences in the conversion factor only for flat collectors. They lead to larger variations with ribbed tube absorbers than with normal tube absorbers.

All absorbers are very easy to handle (see also Chapter 5 on installation): thus for example all common types can be walked on.

Figures 7.5 and 7.6 show respectively a summary of the absorbers available on the market, and the different methods of connecting the absorber to the collection and distribution pipes.

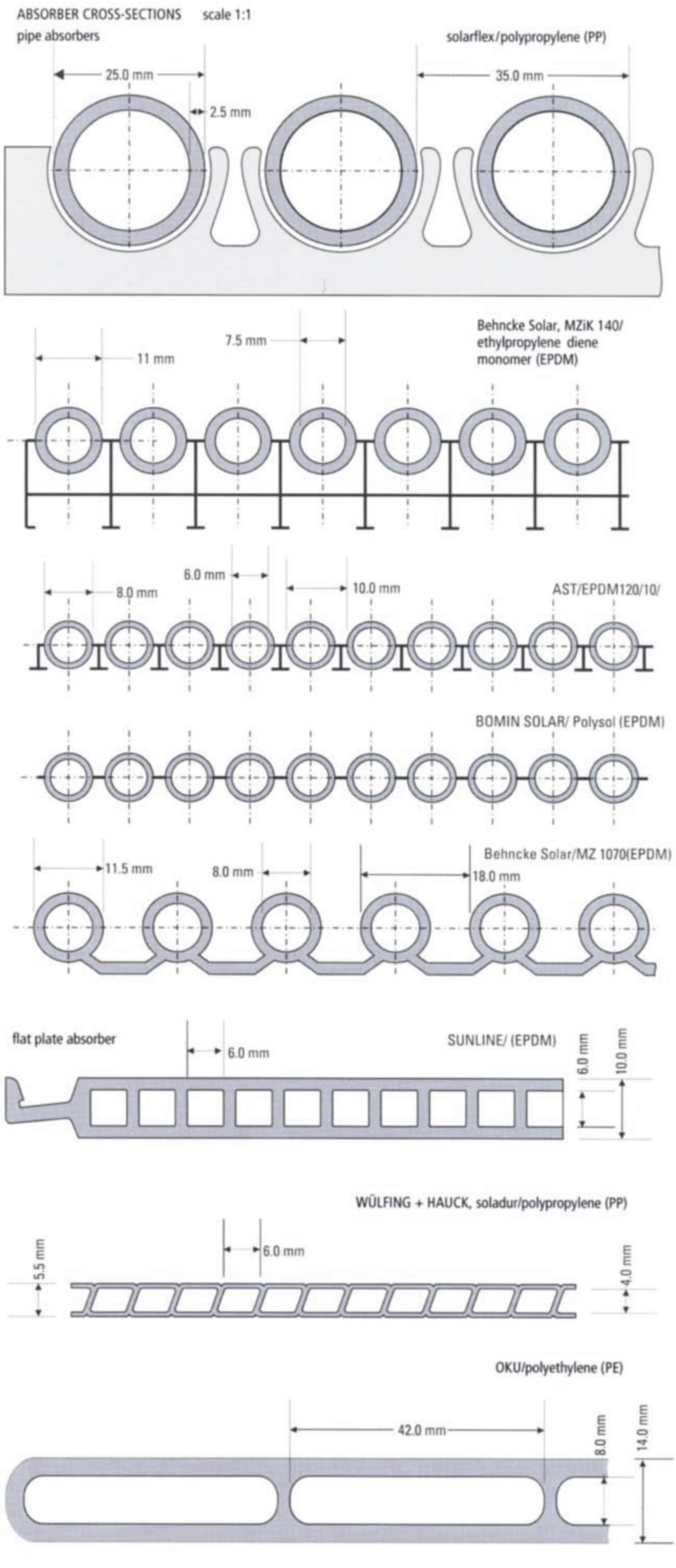


Figure 7.5.
Different designs of absorber in cross-section

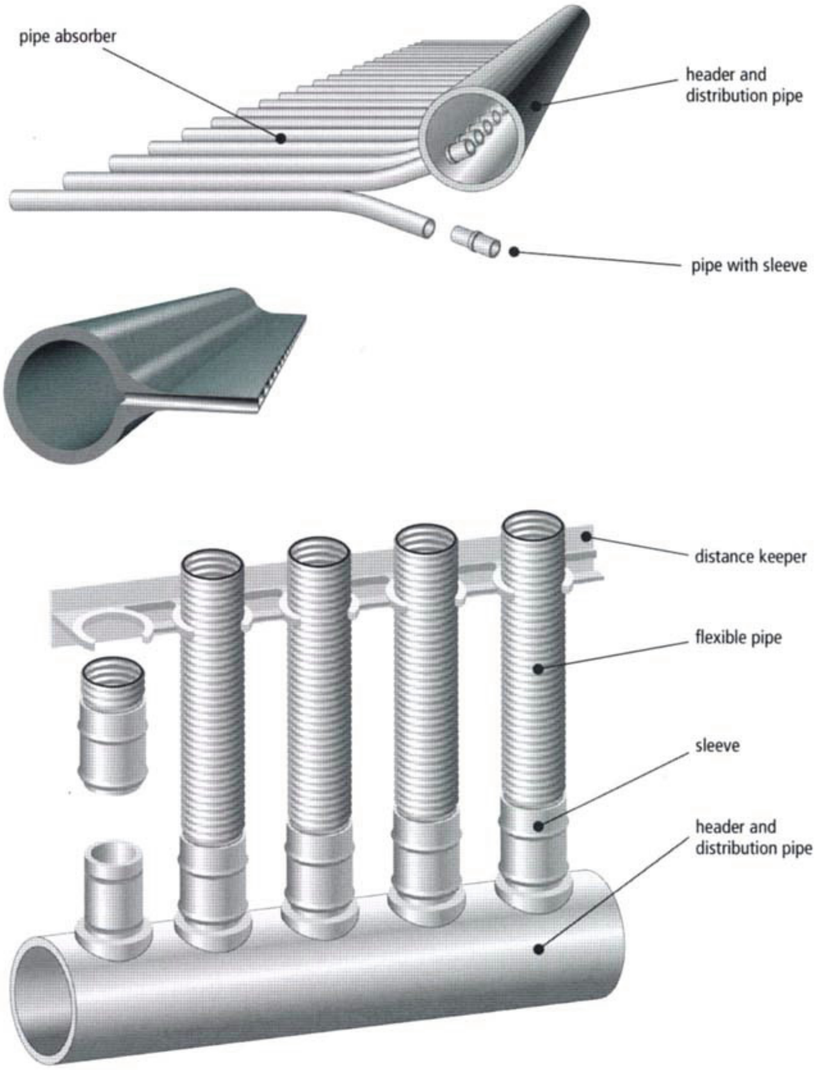


Figure 7.6. Different methods of connecting the absorber to the collecting/distributing pipes

7.2.1.3 PRESSURE LOSS

It is important to consider the pressure loss of the absorber during planning. As the pressure loss for the whole system defines the pumping power, the objective of the designer here should be to achieve the lowest possible system power requirement with the highest possible thermal yield.

In the following we shall therefore discuss briefly the very different pressure losses of the individual absorbers. In general it is true that the maximum permissible excess operating pressure is quite low (0.5–1.5 bar). Only the finned tube absorber has a higher value (3.0 bar). The tube cross-section or diameter has the greatest influence on the pressure loss. When using absorbers with small tube diameters, lower maximum lengths are possible than for absorbers with large diameters. This must be taken into account during system planning.

7.2.2 Piping and header pipes

In principle the same components as used in the solar circuit for solar heating can be used for open-air swimming pool construction. Copper or steel pipes cannot be used here because of the risk of corrosion; plastic pipes are the only ones that can be used.

The header pipes are generally made especially for the particular absorber type and are offered by the manufacturer together with it. Sometimes they are actually integrated directly in the absorber.

According to the system, end-stoppers, sleeves, socket ends and pipe connections are usually offered together with the collector and distributor pipes, which can be fixed by gluing, by welding or – as shown in Figure 7.7 – with clamps. In the case of long straight pipelines very high temperature-related length changes must be taken

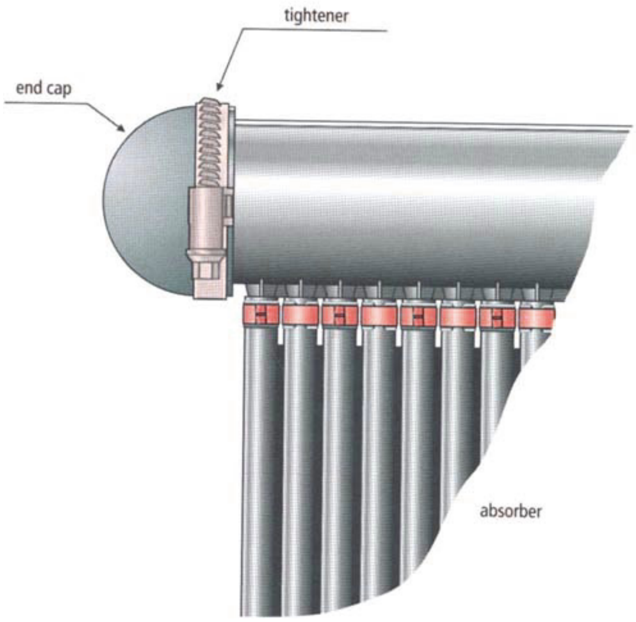


Figure 7.7.
End cap of a collector pipe fixed with clamps

into account for plastics (coefficient of thermal expansion up to 0.2 mm/mK). Appropriate expansion bends must be installed with anchor clamps, which are fixed so that they can slide in the direction of the pipeline (see also section 7.5.2.2).

7.2.3 Materials

Solar absorbers are exclusively made from plastic. They can be hard and rigid or soft and flexible according to the plastic mixture. The use of plastic permits operation of the solar system with chlorinated swimming pool water. It is, however, necessary to consider the chlorine content. A high dose (from about 5 mg/l) can damage the absorber. The exact limits from which damage can occur depend on the composition of the plastic.

Plastics are also used for pipelines. These are made from rigid materials, however. The following plastics are basically the ones that can be used:

- EPDM (ethyl propylene diene monomer)
- PP (polypropylene)
- PE (polyethylene)
- ABS (acrylnitrile butadiene styrene copolymer)
- PVC (polyvinyl chloride – hard or soft).

Because of their good properties, two absorber materials are market leaders in spite of their higher costs: EPDM and PP. Table 7.1 gives a summary of the typical properties of the designated materials for absorbers and pipelines. Both require specific formulations to avoid degradation in sunlight.

7.2.4 Pumps, heat exchangers and other components

7.2.4.1 PUMPS

The materials used for pumps also have to fulfil the requirements for corrosion protection. Because it is normally not possible to use pumps without metal, corrosion-resistant materials should be used. The impeller, for example, is usually made from cast bronze, and the shaft from chrome nickel steel. The housing usually consists of grey cast iron, but plastics may also be used. Some manufacturers also offer swimming pool pumps made completely from plastic, such as glass-fibre-reinforced PP or POM (polyoxymethaline). Pumps can also be obtained on the market in which the pump shaft does not come into contact with the swimming pool water owing to the design. If the capacity of the existing filter pump is not sufficient to pump the swimming pool water through the additional absorber system, one or more supplementary pumps

Table 7.1. Properties of plastics used as absorber or pipe materials

Material	Properties	Deployment temperatures	Lifetime	Deployment
EPDM	– artificial rubber – Flexible, also frost resistant when filled with water	– 50 °C to 150 °C	> 30 years, manufacturer's guarantee often 10 years	Absorber
PP	– Polyolefine – Polymer from Propylene – Pipes weldable – Frost resistant (when not filled with water)	– 30 °C to 120 °C	> 20 to 30 years, manufacturer's guarantee often 10 years	Absorber, piping
HDPE	– High density polyethylene – Weldable – Mostly pipes, rigid – UV resistant through soot – Frost resistant (when not filled with water)	– 30 °C to 110 °C	> 30 years	Piping, absorbers
Soft PVC	– Can be glued – Deteriorates when softeners escape	– 20 °C to 65 °C	Strongly dependent on application	Piping
Hard PVC	– Can be glued, UV resistant	– 5 °C to 100 °C	> 20 years	Piping
ABS	– Polymer	– 10 °C to 80 °C	> 20 years	Piping, distribution piping

must be used. Owing to the large volumetric flow in comparison with domestic water solar systems, and the resulting pipe diameters, the pumps are correspondingly dimensioned and have power settings of several kW, or even more in the case of very large systems (see Figure 7.8).

Figure 7.8. Circulating pump for solar loop, cast iron housing, chrome nickel steel shaft, cast iron or gunmetal impeller. Manufacturer: Herborner, Herborn

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, another 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.

7.2.4.3 OTHER COMPONENTS

According to the system connection, pumps and/or partly motor-controlled valves (Figure 7.9) are necessary for the operation of the system. Plastics are also used here for the valves. Such commercially available fittings for swimming pool systems can be obtained in both PVC and PE or similar materials. As the flow is regulated by motor-

Figure 7.9.
Motor-controlled three-way valve made of PVC. Manufacturer: Resol, Hattingen

controlled valves, some manufacturers of control equipment also offer such fittings for swimming pool system operation. In addition, non-return valves, shut-off valves or slide valves and ventilators are required. These fittings are also standard accessories for swimming pool technology, and are available in correspondingly appropriate materials.

7.2.5 Controllers

A swimming pool absorber system uses the well-known principle of *temperature difference control*. However, the temperature differences that lead to a switching procedure are significantly smaller than in the case of domestic water heating systems, for example. Thus the starting of the solar pump or the positioning of the three-way valve takes place at 2–4 K, whereas at 0.5–1 K the pump is switched off again, or the three-way valve is switched over.

When the pool temperature exceeds a given value the solar system is switched off again. This value can, for example, be approximately 28°C. The maximum temperature should be carefully selected. On the one hand a reduced refreshing effect for the swimmers at higher temperatures plays a role; on the other hand the selected maximum temperature should not be too low, as the pool can act as 'buffer storage' for less sunny days.

The important thing for any form of control is the correct positioning of the temperature sensors. For switching on the absorber circuit pump, the absorber temperature is compared with the pool temperature. However, the pool temperature is not acquired within the pool itself but in the filter circuit. For the most accurate control of the system the on and off signals for the solar systems are separated from one another. This means that the absorber temperature is not used for switching off; instead the feed temperature is compared with the pool temperature. Accurate sensor elements increase the thermal yield of the solar system. As a rule Pt1000 sensors are used. It is, however, also important that the sensors are compared in pairs. It is of secondary importance whether the absolute temperature is accurately displayed.

It has also been found to be useful, especially for large solar systems, to acquire the absorber temperature not by means of clip-on or immersed sensors, but rather by means of a separate non-filled reference absorber section. In this way the effect of the relevant variables of radiation, air temperature and wind is transferred to the output with a very low control delay time.

Controllers for large swimming pool absorber systems can usually also record other variables such as irradiated power and volumetric flow, so that balancing and determination of the efficiency of the solar system can take place. There are also controllers that can operate different pools with different temperature levels. A paddling pool for small children has a much higher set temperature than a swimming or diving pool. If there is low irradiated power and hence available heat from the absorber systems, this can be supplied for example directly to the children's pool, as the thermal output from the absorber is sufficient for this but not for the larger pools.

Figure 7.10 shows a standard control scheme for solar open-air pool heating. Correct positioning and suitable sensors play a decisive role here. Some controllers are also able to control the auxiliary heating. In order to use energy rationally it is particularly important to consider the desired maximum temperature in the case of auxiliary heating. If one chooses a high target temperature the losses increase and hence the energy consumption also increases. If the temperature is raised, for example, from 25°C to 25.5°C the energy consumption increases by up to 10%.

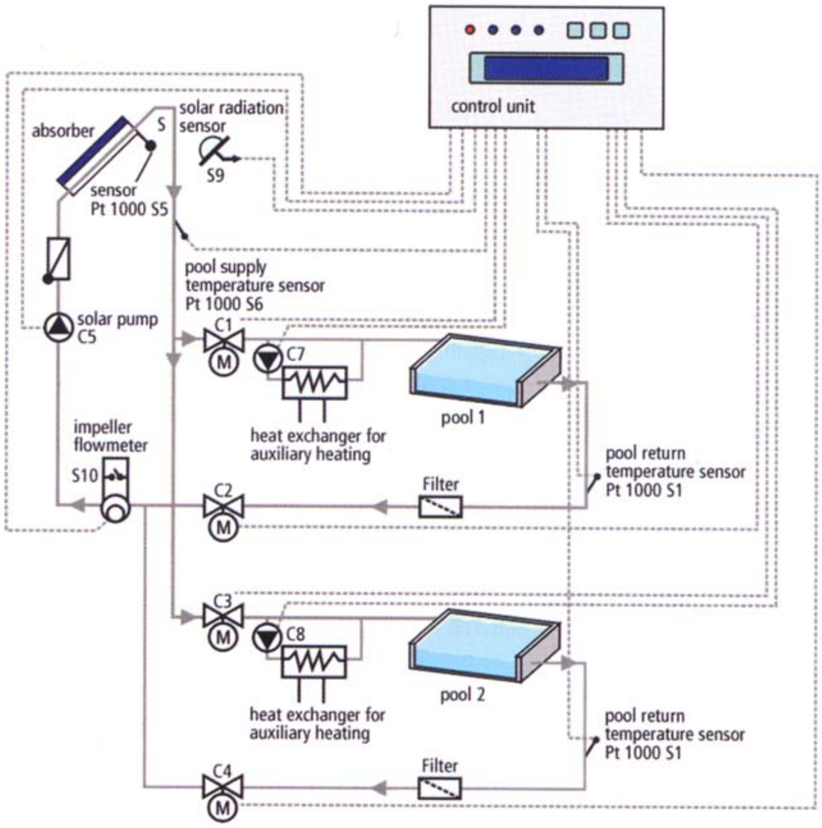


Figure 7.10.
Example of a control scheme for a solar open-air pool heating system

NOCTURNAL COOLING

In hot and sunny weather, normal solar radiation striking the surface area of the pool may result in pool temperatures exceeding the point at which the pool is refreshing. A simple switch can be employed to simply reverse the sensors and trick the controller into engaging the pump and circulating pool water through the collectors. If a clear sky is present, thermal radiation from the pool water can effectively reduce water temperatures and ensure a refreshing pool. In large pools where swimming competition requires temperatures within a several degree threshold, this feature can be very useful for outdoor competition.

7.2.6 Covering of the swimming pool

The heat losses from a swimming pool occur mainly from the surface of the water through evaporation, but also through convection and radiation (see also Figure 7.16). To prevent overnight reductions in the pool temperature a cover over the water surface with a suitable thermal insulating effect is recommended. This prevents up to 100% of the overnight evaporation of the pool water from taking place, and the losses through radiation and convection are significantly reduced too.

A cover is particularly efficient in temperate climates, if the pool water is to be held at a high temperature (> 25°C) or if the pool is in an unprotected position. Here it is possible to save between 30% and 50% of the energy according to the location and position of the pool, or the temperature can be held at a higher level. Because of the considerable extra costs for covering the large pool surfaces in municipal open-air pools these covers are usually not installed.

In the case of private swimming pools, simple and cheap covers can always be installed. The absorber surface can be kept smaller because of the savings due to the covering, and the total investment costs can thus be reduced in spite of the extra costs for the cover. Just like the absorber, the covers should be UV- and temperature-resistant. They also are made of plastics such as, for example, closed cell PE foam, PE bubble-foils or PVC cellular profiles (Figure 7.11). The heat can be significantly better maintained in the pool with PE foam covers than with PVC profiles.

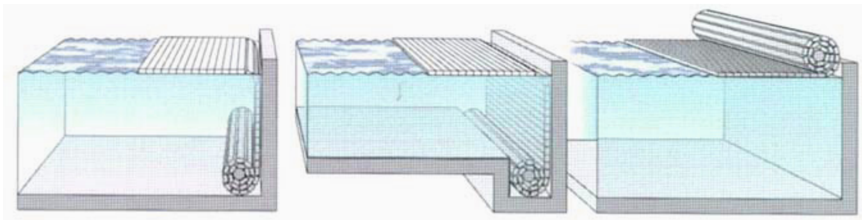


Figure 7.11. Different covering variants for swimming pools to reduce heat losses

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. 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.

7.3.1.1 SYSTEMS WITH THREE-WAY VALVES

The absorber circuit is integrated into the existing filter circuit with a three-way valve (Figure 7.12). This means that the filter pump must be suitably dimensioned in order to overcome the additional pressure loss in the absorber circuit. As a rule this is the case in private swimming pools. It depends strongly on the height difference between the pool surface and the absorber. If this is greater than about 5 m, an additional absorber circuit pump is normally required (see section 7.3.1.2).

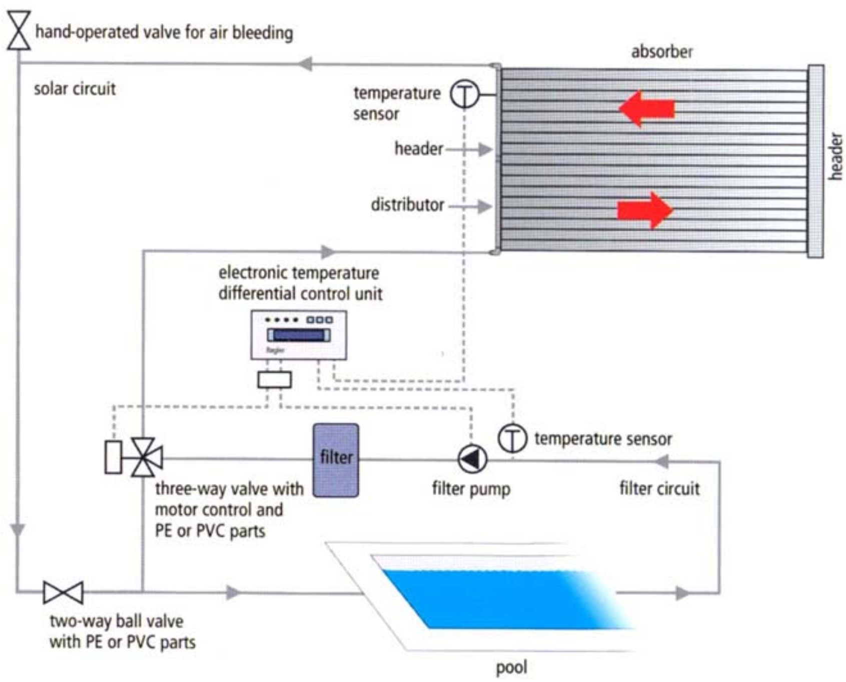


Figure 7.12. Circuit diagram of absorber system with three-way valve

If a suitable temperature difference (2–4 K) exists between the absorber and the pool water, the solar controller starts the pump operation. The motor-controlled three-way valve is set so that the water flows through the absorber, heats up, and is then led back to the pool.

There are even simpler solutions in which the three-way valve is operated manually instead of by the controller. However, these are rarely used.

7.3.1.2 SYSTEMS WITH ADDITIONAL ABSORBER CIRCUIT PUMP

In these systems an additional pump operates the absorber circuit. In the conditions described above, this is switched on in addition to the filter pump. A non-return valve should be installed in the feed to the absorber circuit to prevent the absorber field from running empty after switching off the pump. This can be operated electrically or pneumatically. In such a case a non-return valve should also be installed in the filter circuit to prevent incorrect flows (Figure 7.13).

In a variant without a non-return valve, a set of fans or a ventilation fitting should be installed. If the absorber runs empty when the pump is stationary, a vacuum can occur, which would damage the absorber. A simple ventilating device allows air to flow into the absorber. When the pump is switched on, the air in the absorber is forced out through the absorber and filter circuit into the pool. A ventilating device ensures that the air can immediately escape again from the absorber when the pump is switched on.

In a system with an additional absorber circuit pump there is also an alternative operating mode. If the pool filter circuit is not permanently operated, the absorber circuit can be connected independently of the filter circuit. The pool water is removed in front of the filter system and pumped through the absorber by the absorber circuit pump. For this purpose the absorber circuit pump should have a fine filter connected upstream.

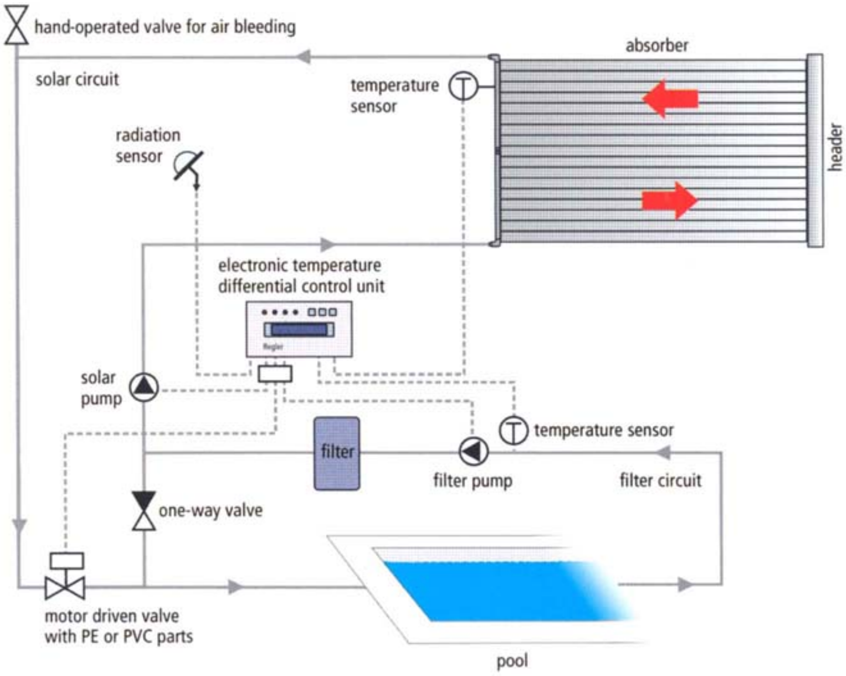


Figure 7.13. Circuit diagram of absorber system with additional solar pump

7.3.1.3 INTEGRATION OF AUXILIARY HEATING

Information on the integration of an auxiliary heating system can be found in the corresponding section for public open-air pools. This also applies to private swimming pools.

7.3.2 Solar heating of public open-air swimming pools

A further application for solar open-air pool heating is that of public pools, which are mostly operated by local authorities, although some are privately operated. Here, according to the type of pool complex, one or more pools are heated by the absorber system. How many, and which pools are supplied with solar heat, depends on the system configuration and the surface available for installation of the absorbers. In large open-air pools an absorber surface area of several hundred square metres can easily be required.

7.3.2.1 HYDRAULIC CIRCUIT

Solar circuits in public open-air pools are normally operated with a separate solar circuit or absorber circuit pump. The hydraulic construction is much more complex than for private swimming pools because of the hygiene requirements.

A system in a large open-air pool functions according to the following principle. The waste water is led from the pool into a central water storage tank. This tank acts as a 'water-level display' for the whole swimming pool water circuit. Evaporated water is replaced here by fresh water. The water is pumped through the filter from the water tank. One or (according to the design of the filter system) several parallel-connected filter pumps are used for this. After this the water is returned to the pool via the water treatment system.

In front of the water treatment system, the absorber field is connected to the circuit in a bypass system. The solar loop pump diverts part of the volumetric flow and pumps it through the absorber field. The size of the partial volumetric flow depends on the size of the absorber field. The solar-heated water is led to the main flow again after the diversion and finally arrives back in the pool.

A motorized valve should be installed in the absorber circuit feed line and a non-return valve after the solar pump. These two fittings prevent the absorber field from running empty when the system is not in operation.

Before the water reaches the pool the hygiene parameters are set. Chlorine and chemicals are introduced to regulate the pH value as necessary. The chlorine injection point should always be integrated behind the absorber field diverter, as the chlorine concentration in the absorber circuit must not exceed 0.6 mg/l. If there is a surge of chlorine (under certain circumstances up to 10 mg/l) the absorber may be damaged.

OTHER CIRCUIT VARIANTS

The hydraulic circuit described above is the most simple and economic. It does, however, mean that all pools must be operated via the same filter system.

If each pool of an open-air complex has its own filter circuit, the absorber system must be integrated in other ways. One option is to connect the absorber field hydraulically to several filter circuits. However, a partial flow must always be diverted from one filter circuit and heated by the absorber system. In this way each pool can be solar-heated successively. For example, at first the swimming pool can be heated, and if additional solar heat is still available this can then be provided to the diving pool.

Other arrangements of the hydraulic circuit allow the supply of the solar-heated water to only one, several or all pools according to the current thermal output of the absorber unit.

When realizing such a circuit, the position of the pools and their filter circuits as well as their distance from the absorber field must be considered for both hydraulic and financial reasons.

7.3.2.2 CONNECTING THE ABSORBER FIELD

With solar-heated open-air pools there is often the difficulty that the absorber field has to be installed on several roof areas. In addition, it is rarely possible for each absorber field to be the same size, and also the pipeline lengths are all different. A circuit conforming to the Tichelmann connection (also called Z-connection, see Chapter 2) is worth striving for, but is usually not feasible. It is therefore even more important for all the absorber fields to have a uniform flow through them. This entails careful arrangement of the pipelines and absorber field pumps. Ball valves should be installed at suitable points to guarantee simple emptying and filling of the absorber fields.

7.3.2.3 HEAT RECOVERY FROM THE REVERSE FLOW FILTER WATER

The filter system must be cleaned at regular intervals, or the filter itself may have to be cleaned after contamination. This is done by a reverse flow of fresh water. The

Next Page

water flushed through the filter must be drained to the sewer, which means that heat is inevitably lost. The fresh water that replaces the water drained into the sewer can be preheated via a heat exchanger. Coaxial heat exchangers with automatically circulating cleaning pellets have proved themselves to be useful for this.

As for other applications, the economics of heat recovery from the reverse flow filter water must be carefully considered. As a rule this is worthwhile mainly for pool temperatures over 23°C. Installations carried out within the scope of a complete restoration of the pipeline system and a long swimming season can also improve the economic viability.

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.

Auxiliary heating is operated by means of a conventional system (preferably gas heating) and an additional heat exchanger. In a dual-heated system the auxiliary heating should always follow the solar heating. If the water is not of the required temperature after recirculation to the filter circuit, the auxiliary heating covers the residual heat requirement (Figure 7.14).

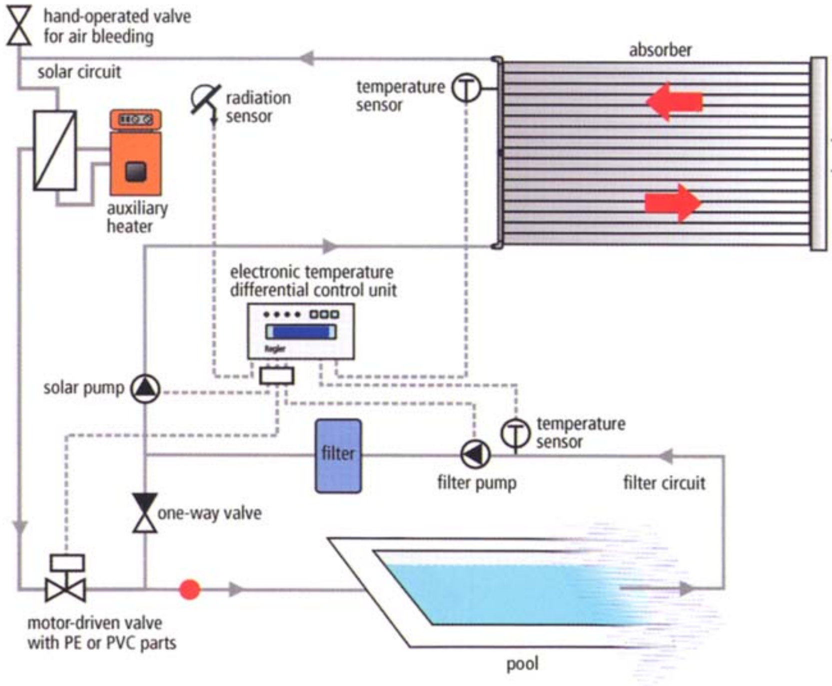


Figure 7.14. Circuit diagram of large absorber system with additional heating

7.3.2.5 RATIONAL USE OF ENERGY IN PUBLIC OPEN-AIR BATHS

Much of the total heat requirement is basically determined by the level of fresh water required. The amount of fresh water is very high in most open-air pools: 10–20 m³ per square metre of pool surface per season are typical figures.[44] Of course, these figures depend on the pool usage. This amount of water has to be heated from the cold water temperature to the pool temperature. In central Europe, this means that about 15–20 kWh of heat is required to heat 1 m³ of fresh water to pool temperature. Whether the amount of fresh water added goes beyond the required level is easily established on the basis of the annual quantity of water consumed if the water is taken from the public drinking water network.

With old filter technology the required quality can be achieved only by the addition of significantly more fresh water, which in turn must be brought up to the required pool temperature. Together with the increased energy requirement of old pumps and the greater flow resistance of older technology, this can represent half of the energy consumption of an open-air pool complex. So by replacing old equipment a significant part of the energy can also be saved.

8 Solar air systems

8.1 Introduction

Air-operated solar systems are comparable with solar systems in which the heat transfer medium is a liquid. However, air as the heat transfer medium in solar systems has very different physical properties from those of water (see Table 8.1), which has marked effects on solar air systems:

- Air heats up faster than water, owing to its much lower heat capacity. This means that in solar air collectors useful temperatures can be reached even at low irradiation levels.
- Energy storage in air systems is more expensive and can only be done indirectly, as the heat transfer medium – air – is itself unsuitable for energy storage.
- Heat transfer from the absorber to the heat transfer medium is worse for a solar air collector than for a similar-sized solar collector using a liquid medium, mainly because of the lower thermal conductivity of air.
- Energy transport by means of air requires higher mass or volumetric flows in comparison with energy transport in liquid heat transfer media. Air systems therefore always require thorough planning and installation to minimize the use of auxiliary energy.

Table 8.1. Some material values for air and water at 25°C and 1 bar

	Air	Water
Density (kg/m³)	1.185	998,200
Specific heat capacity, *c* (mass) (Wh/kgK)	0.28	1.16
Specific heat capacity, *c* (volume) (Wh/m³K)	0.31	1158
Thermal conductivity (W/mK)	0.026	0.559

As a heat transfer medium, air offers the following advantages and disadvantages.

The simple system structure can be seen as an advantage. Unlike systems based on liquids, there are no problems with respect to system safety with air as the heat transfer medium, because of the properties of air. Air cannot freeze or boil: therefore no measures are necessary for frost protection, nor are precautions required for the stagnation situation. Moreover, air is significantly less corrosive than liquids. This also increases the service life of the collectors. A general advantage of using (solar) air collectors when heating habitable spaces is the lower temperature level of the feed air into the rooms, as compared with the necessary higher feed temperature of classical wet-based space heating. It is therefore possible to design for lower temperatures, which has a positive effect on the collector efficiency. In addition, some of the heat transfer losses involved in classical water heating are not incurred.

A disadvantage is that, because of the lower heat capacity and poorer heat conductivity compared with those of liquids, larger duct diameters and exchanger surfaces are required for the heat transfer to other media.

Overall these properties permit a very simple system design for the direct solar heating of buildings, as no separate circuit is required for this task. The air flowing through the collectors can be led directly to the building. Furthermore, the fresh make-up air for buildings can be solar heated, permitting greater volumes of fresh air and improving indoor air quality while reducing or eliminating additional energy needs.

For the sensible integration of a solar air system into a building it is advantageous if a system for controlled (mechanical) building ventilation is already installed; if not, then such a system should be installed. With the low energy requirements of new buildings, and the necessarily thick building skins, controlled ventilation is also installed more frequently in public-sector house building. The lower transmission losses from the house, in connection with heat recovery, can lead to even lower energy consumption. By means of a sensible combination with solar air systems, it is also possible to input solar gain in addition to the energy savings. As both ventilation systems and solar air systems operate with the same medium, it is possible to integrate such a system without great expense. But also when no mechanical ventilation system is installed, it is possible to make use of a solar air heating system.

In passive houses, however, the use of solar air collectors is critical for economic reasons, as the heat energy requirements in spring and autumn are mostly low, owing to the high passive gain. This leads to a requirement for thermal storage, for which the simple and inexpensive solar air systems are less suitable. See Figure 8.1 for an example of a solar air system.

Figure 8.1. Example of a solar air system. Source: Grammer, Amberg

8.2 Components

8.2.1 Collector types

Solar air collectors can be differentiated according to the type of absorber flow pattern, or the type of collector cover.

8.2.1.1 DIFFERENTIATION ACCORDING TO TYPE OF ABSORBER FLOW PATTERN

Solar air collectors can be classified into three types of construction, depending on the way in which the heat transfer medium (air) is brought into contact with the absorber (see Figure 8.2).

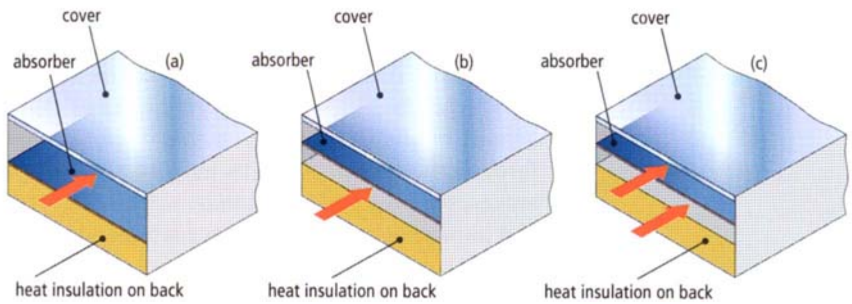


Figure 8.2. Designs of solar air collectors (a) flow over absorber (b) flow under absorber (c) flow on both sides of absorber

The fundamental design is the same for all three basic types. On the back of the collector there is thermal insulation in order to minimize the heat losses to the surroundings. The housing is closed on the front by means of a transparent cover.

In type (a) the absorber lies directly on the thermal insulation. and the air to be heated flows over the top. Type (b) has an air channel between the absorber and the thermal insulation through which the airflows. This prevents the flowing warm air from coming into contact with the cover, which significantly reduces the convective heat losses from the front. Type (c), with all-round flow, is in principle the same design as type (b), but the absorber has the airflow around both the upper and lower sides. The heat transfer from the absorber to the air is improved in this way, but heat losses can again occur on the front side. These three basic variants are covered collectors.

As described in the introduction, the heat transfer from the absorber to the air is poorer than for collectors using liquid media. Starting with these three basic types, many different modifications and further developments of solar air collectors are known. Optimization of the heat transfer is usually the main focus of the development. In assessing these developments, however, it must be borne in mind that the pressure losses should be minimized in the solar air collector. This development leads to optimization problems with the two contrasting objectives of improvement of heat transfer, and minimization of pressure losses.

8.2.1.2 CLASSIFICATION ACCORDING TO COLLECTOR COVER

As for liquid-based collectors, solar air systems also have collector variations in which the most simple and hence inexpensive design is aimed for. A non-covered air collector has a greater heat loss owing to the lack of a transparent cover, particularly with higher absorber temperatures. Its efficiency is thus lower. This design can, however, be of interest if working with lower absorber temperatures. Because the material costs are reduced and the production is simplified, with this type of collector and with suitable boundary conditions very low heat-production costs can be obtained. This type of solar air collector is used mainly for fresh air preheating, for the reasons described (see Figure 8.5). For applications in which higher operating temperatures are needed in the solar air collector, covered solar air collectors are selected.

8.2.1.3 STANDARD AIR COLLECTORS

A standard collector corresponding to type (b) above is shown in Figure 8.3. It has a frame, thermal insulation on the back and sides, a transparent glass cover, and an absorber. The absorber consists of a coated aluminium sheet that is designed as a U-profile. Placed side by side, these profiles produce a ribbed profile for the transfer of the heat to the air that is flowing through.

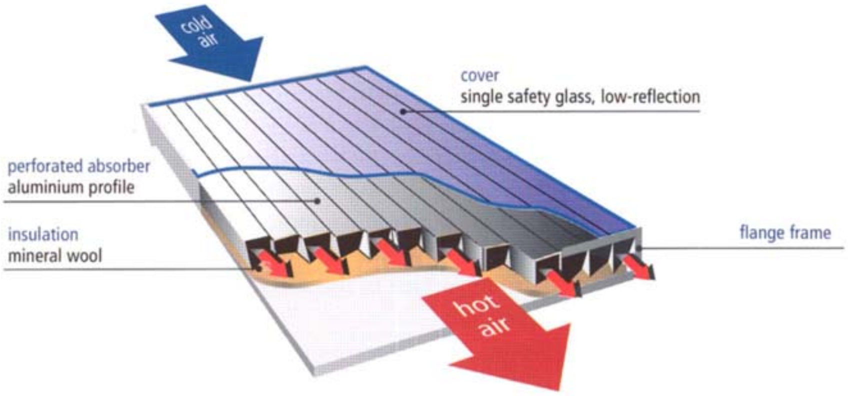


Figure 8.3. Schematic construction of an air collector with under-flow. Source: Grammer, Amberg

The collectors are available in different versions. For example, different depths are offered, depending on the system size. Increased airflow is permitted by the increased depth in larger systems.

In addition, because of the flow-specific series connection of the collectors, there are different modules available. The middle collector is connected on its narrow side to the end collectors by means of flanged connections. The end collectors have an integrated air connection. This connection is either designed as a pipe connection, for example to lead the waste air from a building through the collectors, or it is fitted with an air filter integrated into the rear opening in order to lead fresh air directly through the collectors.

8.2.1.4 ROOF INTEGRATION

For new buildings, or during refurbishment, if it is planned to integrate the collector into roof, the collector area is arranged and installed in modular form. Absorber troughs, whose height is derived from the required airflow (110–170 mm), without a transparent cover are used. They are offered in flexible dimensions of 400–1200 mm by 1000–2500 mm. The collector surface is bordered by the roof-covering frame. For each row of collectors two air-connecting parts are required on the rear wall of the trough. A diverting module is used to provide a side airflow through two collectors. Finally a single pane of safety glass is placed on the absorber troughs. Collectors can also be mounted on flat roofs (see Figure 8.4).

Figure 8.4.
Air collectors placed on stands on the roof of a factory building. Source: Grammer, Amberg

8.2.1.5 OTHER VARIATIONS OF AIR COLLECTOR

To provide independent operation of the air circulation in buildings without a separate power supply (allotments, mountain huts etc.), collectors with an integrated photovoltaic (PV) module can be used. This supplies the electrical energy required to drive a d.c. fan when the sun shines. This variant can, however, also be used on top of dwellings that possess a power supply. The system is then operated by the PV module according to the weather, and no additional costs arise for fan operation.

Regulated back-ventilation of PV modules can also be achieved. The air collector is provided partially or completely with the modules instead of solar safety glass on the front side. The PV modules generate power, which is fed into the network, and the air heated by the waste heat from the modules is used for ventilation or heating purposes. This synergy effect leads to a higher efficiency in the PV module owing to the lower module temperature. Such systems are usually designed as large systems and, for example, are placed on stands on flat roofs. The PV system takes up only part of the surface of the solar air system, and it is not only used for generating the fan power.

8.2.1.6 FAÇADE COLLECTORS

Another interesting application for air-operated solar systems is their integration into facades. Here the collectors can, for example, completely replace the façade in a stud-bolt design, or they can be placed on an existing façade.

As the heating of a building normally takes place in winter and in the transition periods – that is, with low solar elevation angles – vertical arrangement of the collectors has some advantages. For economic reasons, too, façade integration of solar air collectors can be of interest, as during the new building or restoration of a façade costs can be saved in the façade construction. These can then be set against the costs of the solar air collector façade. For the inexpensive integration of solar air collectors into a façade, as well as from the energy point of view, integral planning is of great significance.

8.2.1.7 THE SOLARWALL™ – SYSTEM, TRANSPIRED AIR COLLECTOR

Apart from the façade collector system with transparent glazing, the uncovered collector, which has already been mentioned, is the one that is mainly used (Solarwall system, see Figure 8.5). Here a perforated, dark-coated metal absorber sheet is used as the outside jacket for a façade. By means of regulated suction of the solar-heated air boundary layer on the outer side of the metal sheet, the heat is collected and led to the ventilation system for heating purposes. This simple, direct method can be configured to preheat fresh ventilation air for buildings, thus improving indoor air quality while reducing energy cost. In lower latitudes this same vertical wall can be applied above a roof to capture heat incident on the inclined surface equally well. Applications for drying agricultural crops such as coffee, cocoa and tea have yielded excellent results in many countries.

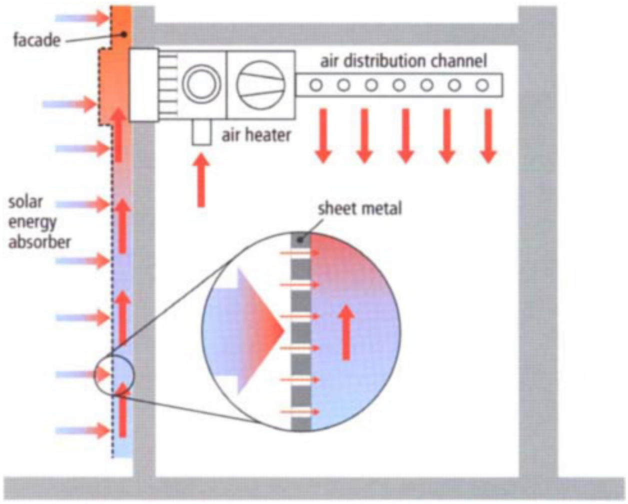


Figure 8.5.
Construction of a solar air system with an unglazed aluminium absorber. Source: Solarwall International Ltd, Göttingen

8.2.2 Fans, blowers

The fans that are normally used in solar air systems are standard trade components as used in normal ventilation systems. In addition to the radial fans that are most frequently used, there are also axial and cross-flow fans. Axial fans can best be used in round pipelines, but they are mainly used in exhaust air systems. Cross-flow fans operate particularly quietly, but have a low air delivery rate and are mostly used only in special cases. Because of its flexible connecting options and its higher delivery rate capacity, the radial fan is preferred (see Figure 8.6). By means of different designs of blade (curved, forward or backward), optimum adaptation to the existing volumetric flows and pressure differences can be achieved.

For solar air systems in factory buildings with very high flow rates, the fans must have power settings of several kilowatts. With an annual average of 2000–2500 operating hours the power consumption required here is significant. In evaluating the additional energy requirement, the pressure loss in the solar air collectors and in the

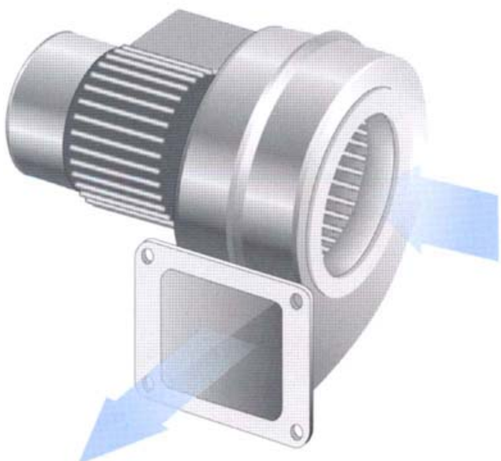


Figure 8.6.
Radial fan

necessary pipes is crucial because of the need to integrate the solar air collectors. With careful planning and design of the system it is possible to reduce the additional electrical energy required to approximately 2–5% of the thermal gain.

8.2.3 Piping

The piping of solar air systems corresponds with the requirements for a normal ventilation system. They must be made from non-combustible materials, and must also be corrosion resistant. The materials mostly used are steel and stainless steel plate. Under certain conditions aluminium is also used. For hypocaust systems (see section 8.3.1.3), apart from the normal wrapped spiral-seam tubes, plastic tubes made of PE or PP are also used for the air passages through the building parts.

Circular cross-sections are mostly used for smaller channels; the pipes are made in a wrapped spiral system. For large air channels square or rectangular sections are normal. The pipelines are mostly available in lengths up to 10 m. They are connected together at the butt joints with gate valves or rebates and clamps; in individual cases they are also welded. Flexible tubes are used to cope with angles that circumvent inaccessible passages and deviate from standard values (connection of collector at inclinations ≠ 45°). Collector connections are additionally provided with thermal insulation. For pipes led outside the building, UV- and weather-resistant heat insulation is recommended. Inside the building this is not necessary.

In order to reduce noise, the use of sound-reducing components is recommended for solar air collector systems. This is particularly true for systems with high user requirements for comfort. High levels of noise occur particularly with high airflow speeds, and also at curvatures because of air friction and because of the use of low-friction wrapped spiral-seam tubes. Therefore, a silencer (see Figure 8.7) is usually installed in front of the room inlet vents in order to reduce the noise load.

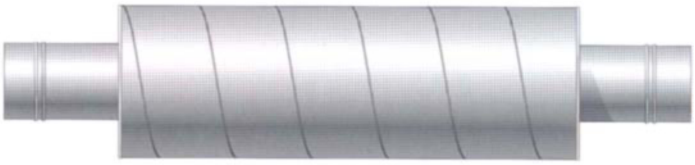


Figure 8.7. Silencer

8.2.4 Heat exchangers, heat recovery units

In (solar) air systems mainly *recuperators* or *plate heat exchangers* (recovery heat coefficient normally about 65% for large flow rates) or *rotary heat exchangers* are in use (see Figure 8.8). These can achieve recovery heat coefficients of up to 90% and simultaneously permit moisture exchange, which can be used for air-conditioning.

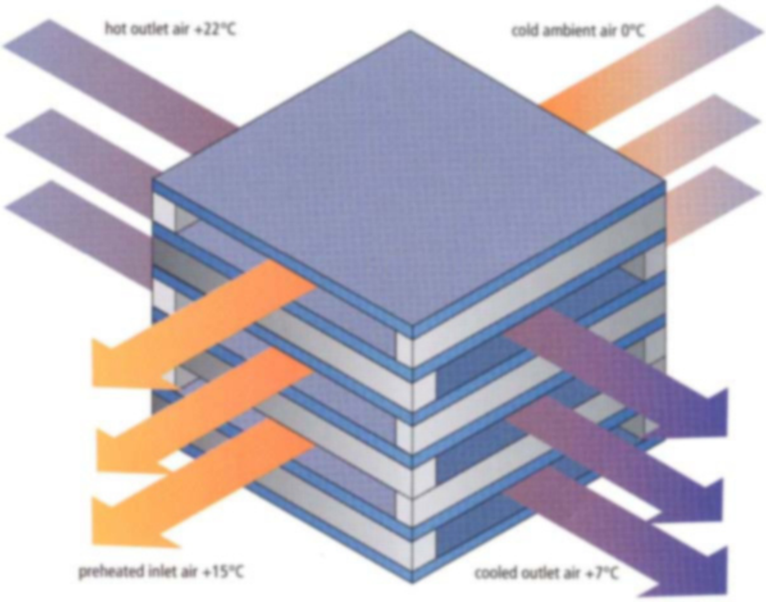


Figure 8.8. Schematic outline of a recuperator with example temperatures

The recovery heat coefficient gives the temperature changes that can be achieved by heat recovery with respect to the outer air or exhaust air side. In the case of devices with simultaneous moisture transfer, there is similarly also a moisture recovery coefficient.

In order to use the excess heat of a solar air system in summer, air–water heat transfer units are used (see Figure 8.9). These can transfer the excess heat to the domestic water and hence make an additional contribution to the reduction of the conventional energy requirements.

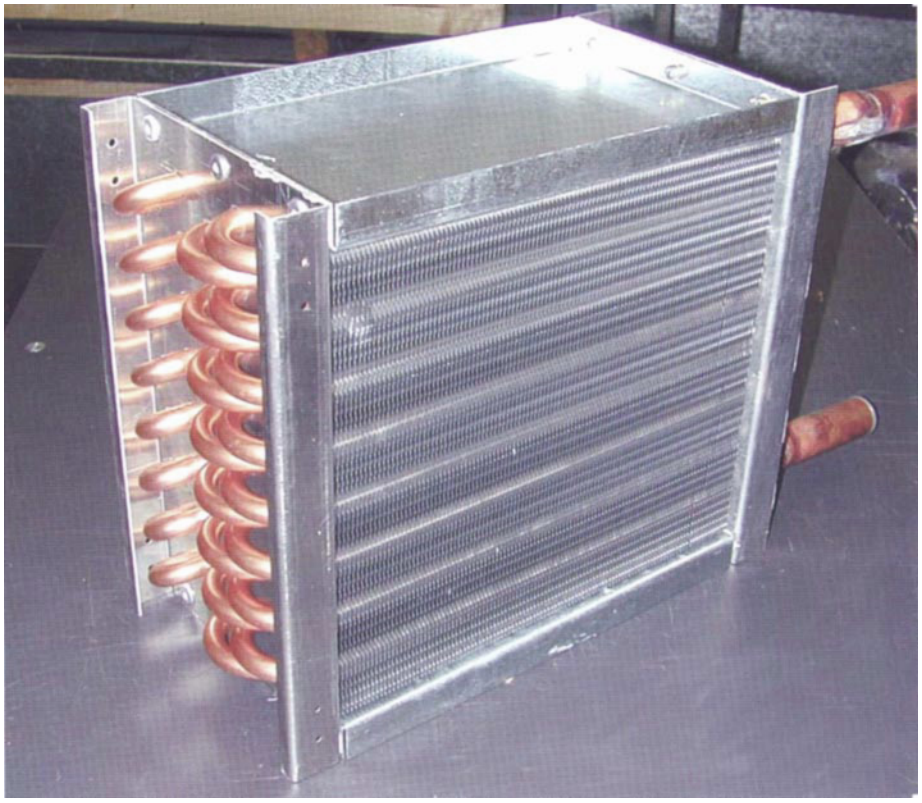


Figure 8.9. Air–water heat transfer units. Source: Grammer, Amberg

8.2.5 Control

Standard temperature difference controllers can be used for the control of solar air systems. The controller compares the room air temperature and the collector temperature. If a given temperature difference (normally 3 K) is reached, the fan is started up. For dual-source heating systems the set temperature of the rooms can be controlled independently of the solar controller by a room temperature regulator installed in the room. Therefore the solar system can raise the room temperature within certain limits above the set temperature of the classical heating system purely with solar energy.

Systems that transfer excess heat to the domestic water require a priority controller. Hot water preparation is then controlled as a low priority. If the solar air system has reached the desired room temperature, the air stream is used for hot water heating (see section 8.3). At times when room heating is not required, the hot water is heated exclusively by solar energy.

For large systems, in buildings with complex ventilation and air-conditioning systems, the solar air system can be linked into the controller for the ventilation/air-conditioning system. Figure 8.10 shows an example of a façade-mounted collector.

8.3 Systems

8.3.1 Air collector systems in housing construction

Air collector systems can be operated in different system configurations. The following can be used in housing construction.

Figure 8.10.
Solar air collector on the façade.
Source: Grammer, Amberg

8.3.1.1 SOLAR FRESH AIR SYSTEM (AIR HEATING WITH FRESH AIR)

This is the simplest sort of solar air system. The collectors have fresh air flowing through them, which is then blown into the building in heated form. There is no exhaust air system; the exhaust air leaves the building by leakage or through exhaust air flaps (Figure 8.11). The required installation for blowing solar-heated feed air into the building is minimal. All that is necessary is to conduct the air into the required rooms. This system is used mostly for retrofitting into existing buildings. If the hygienically required air change is brought into the building via the solar air collector system, every degree of temperature increase brings with it an energy saving. Thus, for example, with an outside temperature of –10°C and a desired room temperature of +20°C, a temperature increase in the solar air collector of only 15 K reduces the ventilation-heat requirement by 50%.

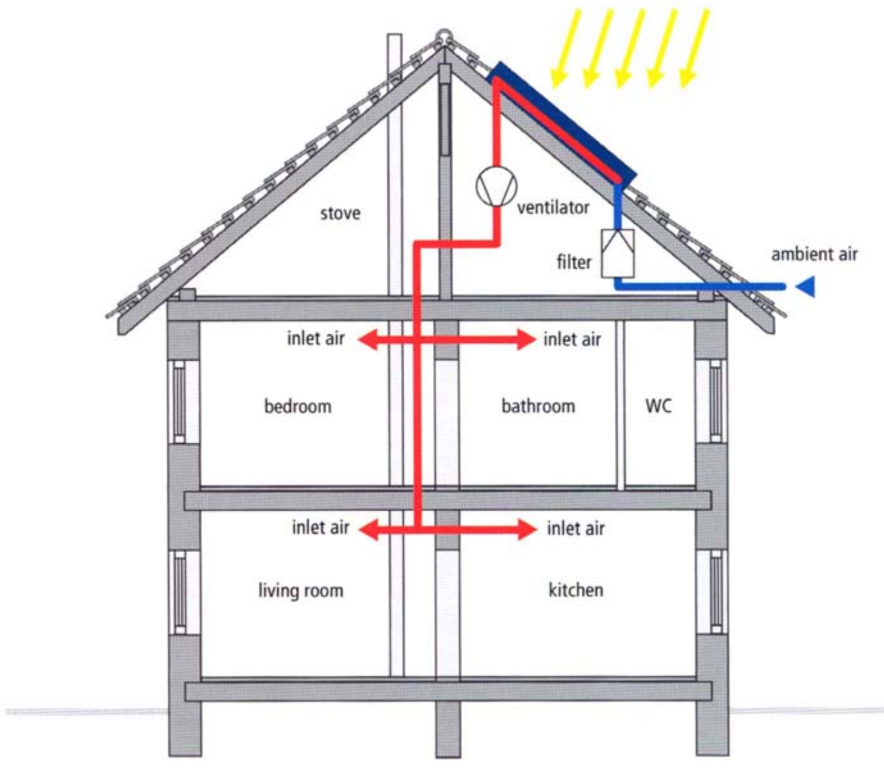


Figure 8.11.
Elementary diagram of a solar air system with fresh air operation

8.3.1.2 SOLAR-SUPPORTED HOUSE VENTILATION

Because of the increasing improvements in the thermal insulation standards of new buildings, the sealing of the walls of buildings is constantly improving. This requires the use of a system for controlling the feed and exhaust airflows, into which the solar air system can be easily integrated. With corresponding solar radiation the fresh air is led through the collectors and heats the building (see Figure 8.12). The heat recovery system provided in many ventilation systems provides additional heating for the fresh air. In more complex systems a portion of the circulated air can be returned to the collectors.

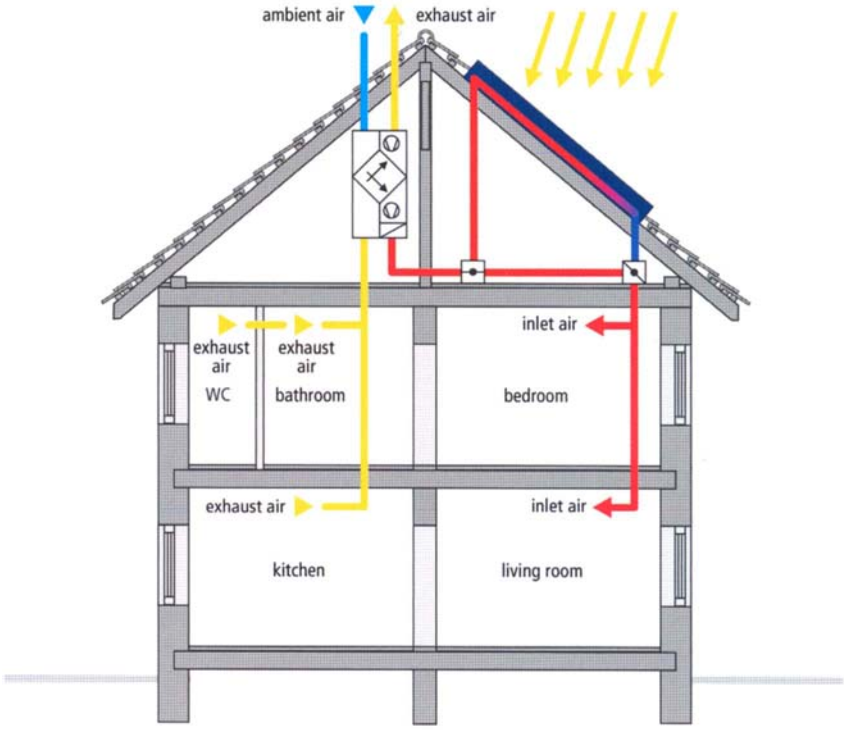


Figure 8.12. Elementary diagram of a solar air system with heat recovery. Shown here is a feed air operation without inclusion of the collectors

8.3.1.3 SOLAR AIR HEATING WITH STORAGE

In order to use solar air heating of a building at times that do not coincide with the solar radiation, the heat must then be stored. This plays a very important role, particularly in dwellings, as heat is required in the evening and at night.

To store the generated heat it must be transferred to a suitable medium. For this purpose gravel or stone storage vessels can be used, for example (see Figure 8.13), but these are usually linked to high costs.

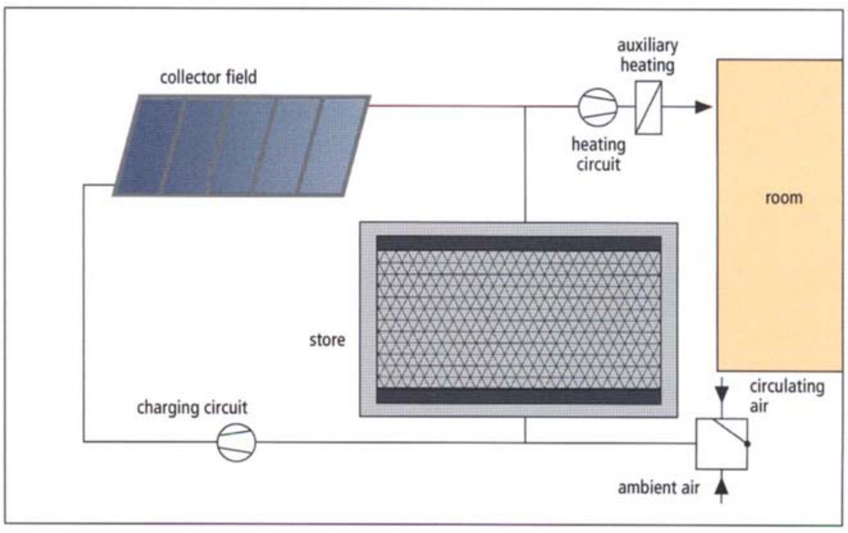


Figure 8.13. Elementary diagram of a solar air system with (stone) storage vessel

A comparatively cheap method of intermediately storing the solar heat is possible with *hypocaust systems* (see Figure 8.14), as long as a solar air system is planned for a building project from the very beginning. Here the warm air stream is led through parts of the building, such as walls or floors. The heat is transferred to the building component, and the component transfers this heat to the adjacent rooms with a time delay. Conventional heating can also be operated via this system in order to use it optimally.

In houses equipped with such a system, the collector surface area is often subdivided. One part feeds the hypocaust system; another feeds a controlled direct room heating system. In this case it is also sensible to incorporate optional switching of the hypocaust system to controlled ventilation, as the corresponding building component can only absorb a limited amount of heat.

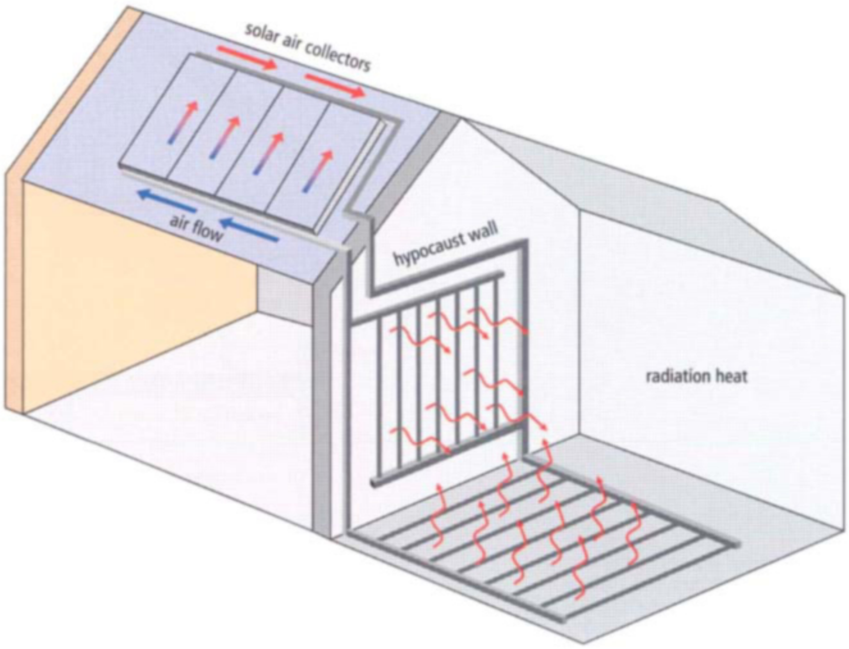


Figure 8.14. Example of a building with hypocaust wall and floor

8.3.1.4 SOLAR AIR HEATING AND DOMESTIC WATER HEATING

A sensible extension of the solar air system is the transfer of excess heat in the sunniest months to the domestic water. In the summer months room heating is normally not necessary, which means there is excess heat available. Between May and September (in temperate climates; November to March in the southern hemisphere) the solar-heated air can thus be used almost exclusively for domestic water heating, and the existing system can thus also be used sensibly within this period.

During the other months the domestic water heating is operated as a low priority, as the air collectors operate more effectively for room air heating and achieve greater solar yields. Once the set room air temperature is reached, a bypass valve is triggered. The system is now operated as a circuit in the same way as for water-based solar systems. The air–water heat transfer unit, which transfers the heat from the air to a separate liquid circuit with safety module and pump, is installed in the bypass circuit. This transfers the heat to the domestic water storage tank via an internal heat transfer unit (Figure 8.15). The liquid-based circuit is operated with frost protection as, otherwise, frost damage to the heat transfer unit can occur at air temperatures below 0°C.

A two-storage control system is necessary to control the system. The cost–benefit ratio for this additional investment for the heat transfer unit, domestic water circuit and safety module must be critically checked, but for most systems can be seen as being worthwhile.

8.3.1.5 SOLAR AIR SYSTEMS IN LOW-ENERGY HOUSES

In new, very well-insulated buildings in temperate climates, it is almost possible to dispense with conventional room heating (combustion of fossil fuels) where a solar air system is installed. Because of the low heat requirement, the solar system can often

Next Page

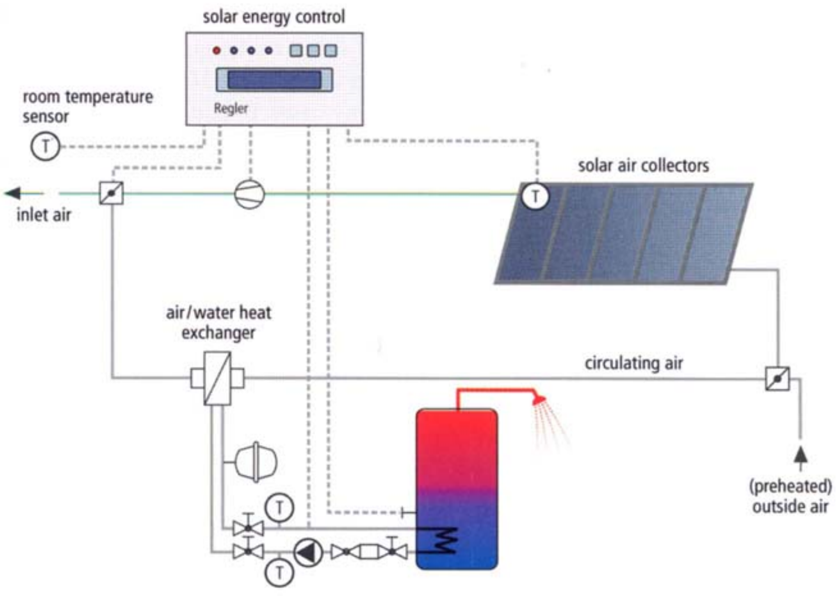


Figure 8.15.
Basic diagram of a solar air system integrated into the domestic hot water system

supply the necessary heating energy in combination with a heat pump as a heat recovery system. However, it is necessary to consider here the primary energy balance in connection with the number of hours of operation of the heat pump over the year. For safety, low-temperature electrical convectors can be installed to cover the residual heat requirement on very cold days.

The system set-up is similar to that shown in Figure 8.16, but instead of the recuperator or rotary heat transfer units, the heat pump is used for heat recovery.

Because of the very low energy requirement of low-energy houses, it is still necessary to weigh up whether a solar air system should be installed. Because of the significantly higher proportion of hot water treatment in the total energy requirement, a solar thermal system for domestic water heating may well be more sensible under these circumstances.

For so-called passive houses (heat requirement ≤ 15 kWh/m^{2}a) the use of solar air systems is often found not to be worthwhile, as their energy requirement is very low even during the transitional periods. The solar air system would only provide good yields in three or four months of the year.

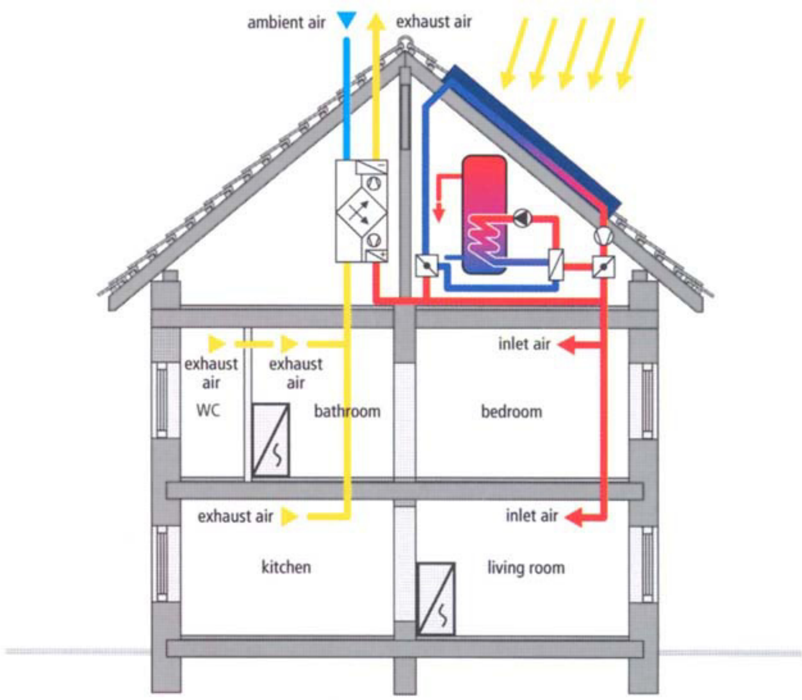


Figure 8.16.
Basic diagram of a solar air system with heat recovery (heat pump) and domestic water heating

9 Solar cooling

9.1 Introduction

The growing desire for comfort has led in recent years to a considerable worldwide increase in the number of buildings with air-conditioning. This trend can also be observed in Europe, and particularly in southern Europe. A similar development can be seen in the automobile industry, where a steadily growing number of cars now have air-conditioning. This is leading to a vast increase in the number of people who are used to living in a climatized environment, and such an environment is also desired and expected at work or at home. Moreover, the results of investigations show that the working capacity of human beings significantly decreases with room temperatures above 24°C.

As the energy consumption of air-conditioning systems is relatively high – and standard refrigeration-based compression systems use electricity – future-oriented solutions for a sustainable energy supply demand renewable energy systems.

Producing cooled air by making use of solar power may seem paradoxical at first sight. Generally, the sun tends to be viewed as a source of heat. However, there exist thermal processes to produce coldness, in which water is cooled or air-conditioning is driven directly by a heat input. These processes are generally suitable for using heat provided by solar thermal collectors as the principal source of energy. Of course, solar radiation can also be converted to solar electricity by photovoltaic systems to drive conventional refrigeration compression systems. However, the latter approach will not be dealt with in the following section, for several reasons:

- In the short term, generating solar electricity in northern and central Europe will be more costly than producing solar thermal heat (exceptions are very small-scale applications, in the range of a few watts up to several hundred watts).
- Although the commonly used refrigerants for compression refrigeration systems generally no longer harm the ozone layer of the atmosphere, they still intensify the greenhouse effect significantly. Compared with CO_2, today's refrigerants could

Figure 9.1. 100 m² collector system for a solar-powered air-conditioning system in Freiburg, Germany. Source: Fraunhofer ISE

potentially boost the greenhouse effect several thousand times over. Thus these refrigerants contribute considerably to the anthropogenic global warming of the atmosphere.

- The refrigerants used in commercially available thermal refrigeration systems contain only substances that do not influence the greenhouse effect. Adsorption- and sorption-based systems just use water as the only refrigerant.

To date, the traditional design of solar thermal collector systems for providing hot water in moderate climate zones such as central Europe has generally been based on the idea that excess heat in summer should be avoided, or at least kept to a minimum. With the systems increasingly deployed in recent years to support heating, a summer excess in principle cannot be avoided. For reasons of economy – the specific collector yield falls with the increasing degree of solar fraction – a larger collector surface is often also rejected, even if this would ultimately be associated with greater environmental relief.

The use of the summer excess heat for solar thermal cooling therefore offers the opportunity to improve the efficiency of solar thermal systems for providing hot water or heating support. Moreover, the new application largely eliminates system shutdowns with the high shutdown temperatures that are a stress on materials. In addition, a promising new application field results for the solar thermal industry. There are also corresponding export opportunities to countries where room air-conditioning is already standard today on account of the climatic conditions.

In this chapter, we repeatedly make a distinction between cooling and air-conditioning. By cooling we mean reducing the temperature, for example in a room or even the temperature of a machine in industrial processes. By air-conditioning, on the other hand, we mean the 'conditioning' of rooms in respect of their temperature and humidity properties, so that people in the room feel comfortable. Hence the term 'air-conditioning' is drawn wider and comprises, in addition to lowering or raising the room temperature in summer and winter, a reduction or increase in air humidity in the room to comfortable values. Despite this distinction, in industry circles the term *solar cooling* has become entrenched as the umbrella term for talking about solar-driven cooling and air-conditioning. Hence if we say 'solar cooling' in this chapter, we 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.

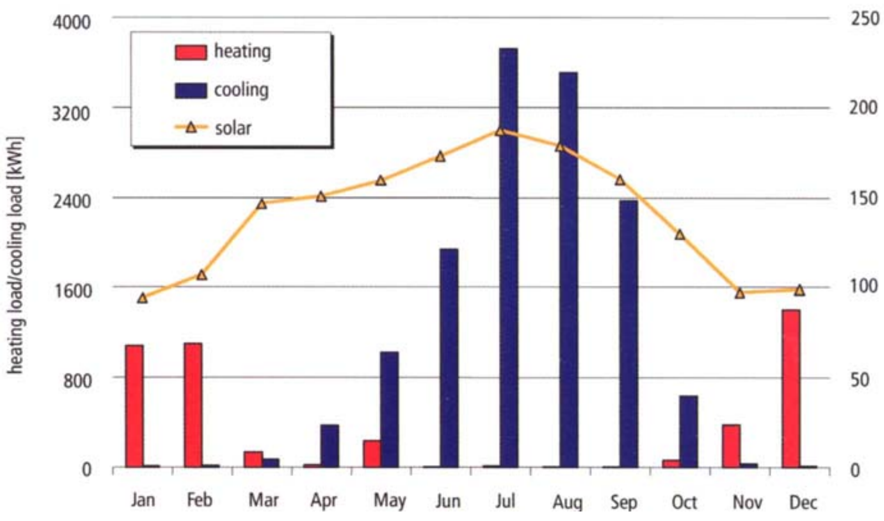


Figure 9.2. Correspondence between solar irradiance and cooling load/heating load for a seminar room in Perpignan (southern France). Source: Fraunhofer ISE

9.2 Theoretical bases

This chapter is intended to give an overview of the processes for solar thermal cooling. It will become apparent that the greatest challenges lie in the system integration of collector installation and cooling technology. As a result, so far there has been a real shortage of planners who are able to plan a solar cooling system from scratch. However, compared with designing a solar thermal system for domestic water heating, the planning task is also much more complicated. The task requires knowledge in very different areas, from building systems to collector technology to cooling systems. In addition, so far there has been very little practical experience with the technology. Some of these systems are presented in this chapter.

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.

Table 9.1. Overview of thermally driven cooling technologies

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.

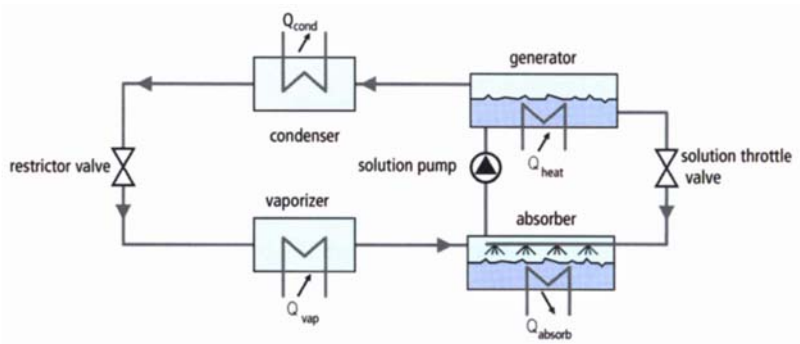


Figure 9.3. Diagram of an absorption chiller[46]

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.

The cooling part of the AbCh is no different from a conventional compression chiller. The necessary compression of the cooling medium to the condenser pressure is performed by the thermal compressor. The vaporized cooling medium flows into the absorber, where it is absorbed by the solvent. The released absorption enthalpy must be dissipated, as the absorption capacity of the solvent decreases as the temperature rises. The absorption process enriches the absorption medium with cooling medium. The rich solution is pumped using the solution pump to the generator (also known as a de-aerator or boiler). Here, by supplying thermal heat, the cooling medium is separated from the solvent and the two-substance mixture becomes depleted of cooling medium. The depleted solvent is depressurized in the solution throttle valve to the absorber pressure, where it is once again atomized in order to absorb the cooling medium.

Apart from the electrical power requirements of the solution pump, the AbCh is driven only by thermal energy. However, the energy requirement of the solution pump is very low, with approximately 0.5–2% of the refrigerating capacity achieved in the vaporizer. The efficiency of the AbCh shown in Figure 9.3 is usually improved by installing a solvent heat exchanger. This is arranged so that the rich, cold solution after the absorber and the warm, depleted solution after the generator flow in opposite directions through the heat exchanger. This makes possible savings on thermal heat in the generator and on cooling water in the absorber.

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.

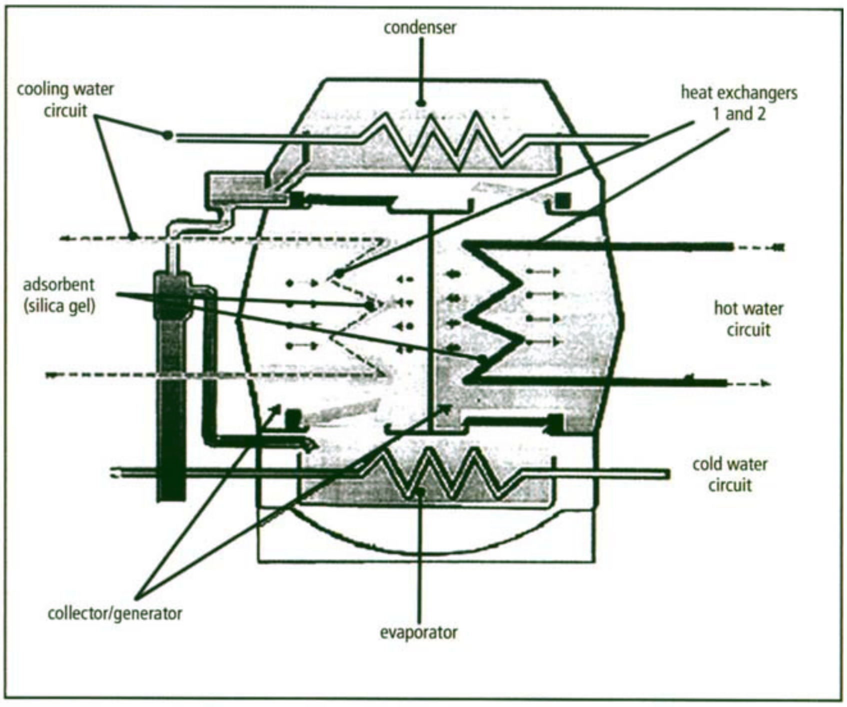


Figure 9.4. Design for a low-temperature adsorption chiller[47]

The AdCh essentially consists of a vacuum tank divided into four chambers. These are the evaporator (lower chamber), the generator and collector (middle chambers), and the condenser (top chamber). The generator and collector are each linked by flap valves, which open and close fully automatically as a result of the prevailing pressure differences in the chiller, to the condenser above them and to the evaporator below them. The AdCh uses water as the cooling medium and silica gel as the adsorbent. The physical properties of water and silica gel are used to produce refrigeration. At low pressures, water vaporizes at low temperatures and silica gel can bond large amounts of water without loss, reversibly and without increasing in volume, and release the water again when heat is applied.

The chiller is fully automatic in a working cycle of 5–7 min that essentially comprises the following four steps, which take place simultaneously. In the first step, water is injected into the evaporator, where it vaporizes. Heat is taken away from the cold water circuit. In the second step, the vaporized water is adsorbed in the collector. This process lasts until the silica gel is saturated. Then it is switched to the second adsorber chamber. In the following third step, the adsorbed water is desorbed after the application of thermal energy. The collector becomes the generator. In the fourth and final step, the desorbed water is condensed in the condenser. The condensation heat is dissipated via a cooling water circuit (recooling system). The circuit is completed as the condensed water is fed back into the evaporator through a valve.

A central characteristic of the AdCh is that the collector and generator are alternately heated and cooled, with the chiller therefore working discontinuously. Thus, alternating periodically, one side is cooled by the flow of cooling water in order to dissipate the heat arising from the adsorption, while the generator is heated for desorption. The periodic change is controlled via pneumatic valves. The chiller is controlled by measuring the cold water exit temperature. An advantage of the AdCh process compared with the AbCh is that it is not limited by a crystallization limit of the solvent.

Adsorption chillers are a new technology, currently with only a few demonstration projects in operation, and in the first market introduction phase. In respect of the use of AdCh for solar cooling, it is of particular note that they can be used to produce cold with temperatures starting from 55°C. Hence both evacuated tube collectors and high-end flat-plate collectors are suitable as solar thermal energy converters.

9.2.4 Desiccant cooling system

In contrast to the absorption and adsorption processes, the desiccant cooling system is termed an open process, as here the air is conditioned by coming into direct contact with the cooling medium. Water is used as the cooling medium, which gives this technology excellent environmental characteristics. In addition, the sorbent – either solid or liquid – also comes into direct contact with the conditioned air. This achieves the required dehumidification of the air.

9.2.4.1 DESICCANT COOLING SYSTEM USING SOLID SORBENTS

Figure 9.5 shows a diagram of a desiccant cooling system (DCS). Compared with a conventional air-conditioning system, the additional components – the desiccant wheel, the regeneration air heater, and the humidifiers for the extracted air and the incoming air – are integrated. On the other hand, the supply air cooler is no longer needed if the necessary scope of dehumidification can be completely implemented by the sorption wheel. A chief characteristic of desiccant cooling systems is that the dehumidification and cooling stages, which in a conventional air-conditioning system take place in one step at the air cooler, are separated.

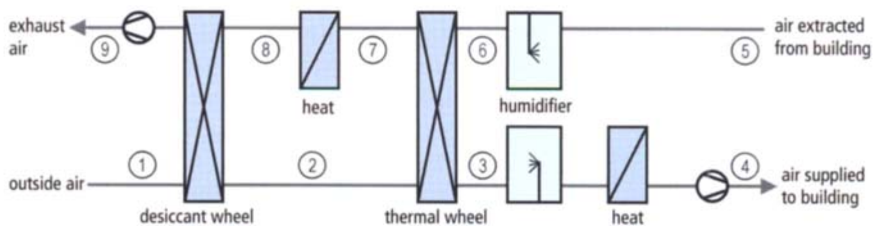


Figure 9.5. Diagram of a DCS system with desiccant wheel[46]

Figure 9.6 shows the process (summer usage) of a desiccant cooling system in a temperature/humidity diagram. The isopleths (lines of the same relative air humidity) are shown as a set of curves.

First of all, outside air is sucked in and dried as it passes through the dehumidification wheel (1–2). The stream of air is warmed at the same time by the adsorption heat that is released. In the thermal wheel (2–3) that comes next, the heat is transferred to the exhaust air or cooling energy is recovered from the exhaust air, and hence the dried incoming air is pre-cooled. In the supply air humidifier (3–4), the air is humidified and cooled adiabatically. The additional heat exchanger before the supply air humidifier is provided only for the heating scenario. The dried, cooled air is supplied to the building and undergoes slight warming in the ventilator (usually 0.5–1 K). As a result of sensitive and latent cooling loads in the room, the room air becomes warmer and is extracted from the room as warm, moist air (4–5). The extracted air is then humidified in the exhaust air humidifier until it is close to the dew point, in order to utilize the cooling potential of the extracted air (5–6). This

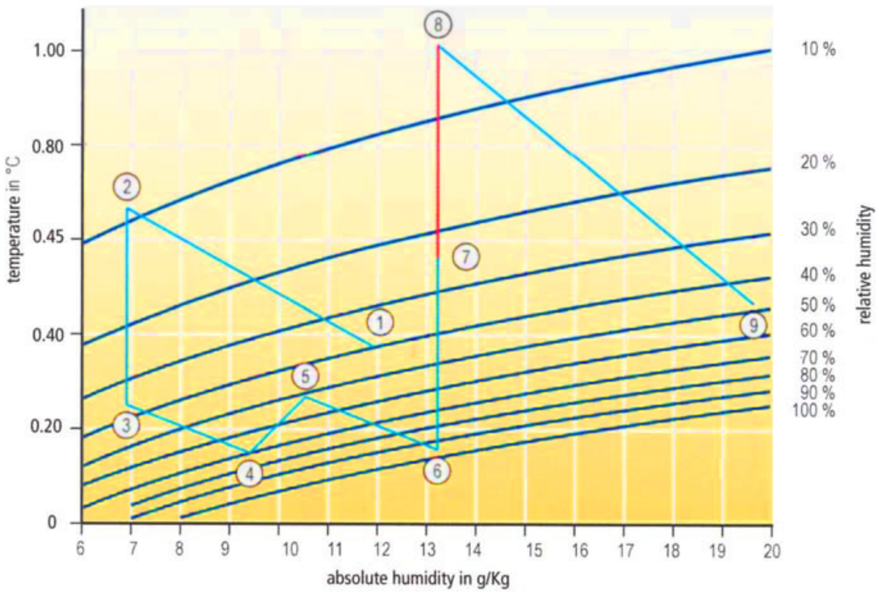


Figure 9.6. Process diagram (summer) of a DCS system with sorption rotor. Source: Fraunhofer ISE

cooling energy is then transferred to the supply air via the thermal wheel (6–7). In order to regenerate the desiccant wheel, the exhaust air has to be heated sufficiently so that it is able to strip the moisture from the wheel. An external heat source is required at this point in the process (7–8). The heated exhaust air flows through the regeneration side of the desiccant wheel as regeneration air, where it strips the moisture taken up from the outside air (8–9).

9.2.4.2 DESICCANT COOLING SYSTEM USING LIQUID SORBENTS

As well as the desiccant cooling system using solid sorbents, which has been established in the market for several years and for which there are already several hundred systems in operation in Europe, there is also a desiccant cooling system that uses liquid sorbents. This process is still under development, and the first pilot systems are currently being tested in Germany and in Israel[48,49]. It is unlikely that a fully developed product will appear on the market before 2005.

As the name implies, the essential difference is in the physical state of the sorption material. In systems that use liquid sorbents, there is a preference for using water-based salt solutions (for example LiCl or $CaCl_2$). The results of various independent investigations have shown lithium chloride to have the greatest potential in respect of practicality. When selecting the optimum salt solution, as well as the purely thermodynamic properties, aspects such as corrosiveness and cost are of course also important.

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.

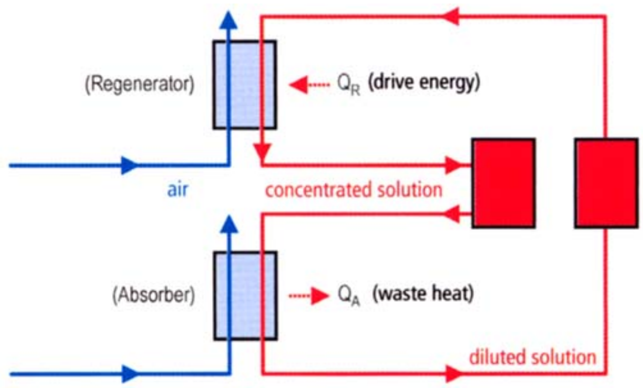


Figure 9.7. Operating principle of a DCS system with liquid sorbents

The conditioned air is dehumidified in the absorber. Here the air is brought into contact with the liquid sorbent. Because of its highly hygroscopic properties, the sorption medium absorbs the water vapour that the air contains, thus becoming diluted. In the absorber, the heat – referred to as *absorption enthalpy* – is released, and this has to be removed. If this heat were not carried off, there would be a sharp rise in the temperature of the solution, and the absorption process would gradually be disrupted. In practice, the released absorption heat can be removed either directly in the absorber or in a heat exchanger downstream of the absorber. Thus, in the *absorber*, with the removal of heat there is a *reduction in the concentration of the water-based salt solution*.

In the regenerator, the concentration of the diluted salt solution is increased. For this, the diluted salt solution is brought into contact with the air again. Outside air is generally used for this process. In the regenerator, heat must be supplied to the process. As the required driving heat needs to be available at temperatures of 'only' 60–80°C, the integration of solar thermal energy suggests itself strongly here. Thus, in the *regenerator*, with the application of heat there is an *increase in the concentration of the water-based salt solution*.

The water-based salt solution therefore travels round a circuit, in principle, but comes into contact with air in the absorber and regenerator. In order to prevent the loss of salt – but also the associated potential corrosion problems in air ducts – one of the most pressing tasks in the development of this technology is to prevent the discharge of salt in the absorber or regenerator (known as *carryover*). This has a marked influence on the design of the absorber and regenerator. Both are essentially very similar in structure. The main task consists of bringing the air and the salt solution into contact with each other, either in counter-flow or in cross-flow, in such a way as to ensure good mass and heat transfer properties and at the same time prevent droplet formation.

Apart from these development challenges, solar air-conditioning (SAC) technology using liquid sorbents does, however, have some significant advantages over SAC using solid sorbents:

- Isothermal dehumidification of outside air is possible. Because it is possible to remove released absorption heat directly in the absorber, it is therefore possible to dehumidify the air being conditioned without causing an increase in temperature. This is impossible, even in principle, with sorption wheels. As a result, significantly higher dehumidification ranges can be achieved with the same air temperatures, or, with the same dehumidification ranges, significantly lower supply air temperatures are possible.
- Heat recovery between the released absorption heat in the absorber and the required driving heat in the regenerator is possible in principle. This enables the thermodynamic efficiency of the process to be increased.
- Because the sorption material is liquid, it can be used at a later time in the absorber or regenerator if solution reservoirs are installed. This first allows dehumidification even if there is no solar energy available at the time. Second, solar energy can be stored in the form of concentrated salt solution (see Figure 9.7). This is particularly promising as *this type of solar energy storage is in principle free of losses*. Hence this technology offers the potential to significantly reduce the required collector surface while keeping the same high solar fraction and hence helping to improve the cost-effectiveness of the solar air-conditioning system.

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.

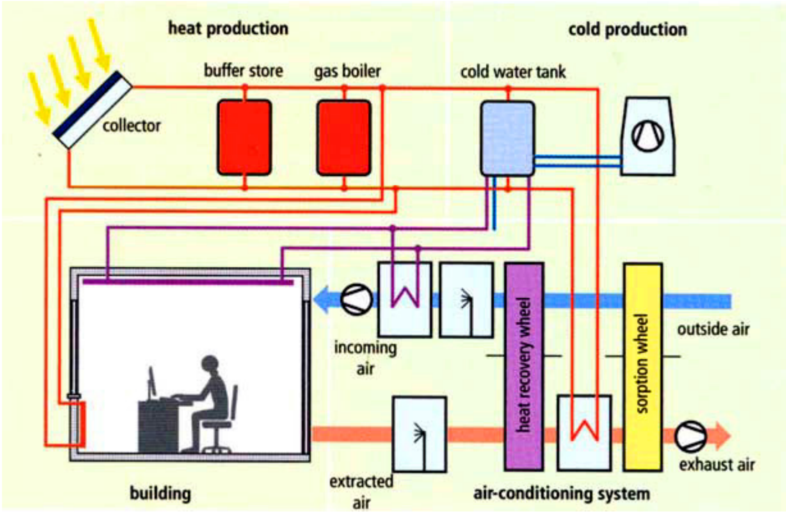


Figure 9.8. Subsystems of solar air-conditioning. Source: Fraunhofer ISE

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).

The greatest challenge is to connect these systems together in an intelligent way. Hence, to achieve an overall concept optimized in terms of energy and economics, integrated planning with good communication between the various disciplines from the beginning is very important.

In air-conditioning for buildings there is no silver bullet – instead there is only the particular customized and optimized solution for each site. At the same time, climatic conditions are also very important, and there is a demand for set-up variants adapted to the climate. Designing a system using rules of thumb, as for solar thermal domestic hot water supply, entails a number of difficulties and at best only allows the basic variables to be determined.

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.

(a) Calculate the hygienically necessary rates of air change for the air-conditioned rooms. In this way, for example, it may be possible to do without mechanical ventilation completely for air-conditioning in an IT room in which people spend only short periods of time. This makes big reductions in investment costs, as in this case the air-conditioning subsystem can be completely eliminated. For rooms where only very low rates of air change are required, check whether these could be implemented via appropriate cross-flow openings from other rooms or possibly by window ventilation. In this context, check whether window ventilation, if it were possible in principle, would nevertheless result in unacceptable working conditions because of noise pollution (for example close to busy streets). Generally workplace guidelines should also be followed.

(b) If mechanical ventilation as at (a) is deemed to be necessary, then see whether this can be implemented with a pure supply air system or with a pure air extraction system. In this case, include appropriate cross-flow openings in the façade and/or partition walls to corridors/adjacent rooms in plans. From the point of view of investment costs, these types of simplified system should be examined in every case and, if need be, should be compared with the resulting operating costs. This can lead to different system decisions, depending on the climate zone.
(c) Check whether splitting the air-conditioning system into different zones would be a good idea. In some circumstances this can lead to large cost savings. In this context, examine in particular the possibility of bringing together locally those IT units that produce large quantities of waste heat.
(d) Examine measures on and in the building to reduce the cooling and heating loads, and incorporate these in the planning. Generally, for buildings that have large areas of glazing, the possibility of an external sunshade system should always be investigated. This measure brings a very considerable reduction in cooling loads in the building, and it is cost-effective. Calculate the resulting cooling and heating loads for the building. It is highly recommended as well to take into account the partial load characteristics in respect of the heating and cooling load from the beginning, as the system operates with a partial load for the greater part of the year and hence this has the greatest influence on the energy consumption of the system as a whole. For more complex building structures, building simulation calculations are always a good idea.
(e) Check what requirements exist for the building in respect of flexibility of the type of use in the expected lifetime of the air-conditioning system. This question can have a very strong influence on deciding the type of air-conditioning technology.
(f) Check what temperature and humidity limit values will be desired and accepted in the building. Moreover, check whether it is acceptable to users and the technical process to exceed or fail to meet these temperature and humidity limit values for a particular number of hours per year. Checking this point can in some circumstances dramatically reduce the investment costs.
(g) Select the air-conditioning technology that is right for the particular use of the building (here questions such as the presence of toxic exhaust air, for example, should be checked as well) and the climatic zone (here it is quite possible that, for large buildings, different solutions will be found for different zones).
(h) Check whether, and which, thermally driven cooling systems come into consideration in principle. Check possible (partial) shading of the collector field.
(i) Check whether cost-efficient waste heat is available at the required temperature level, and whether the heating energy available from the waste heat is sufficient.
(j) Check to see which solar technology comes into consideration in principle for the appropriate cooling technology.
(k) Produce a rough design of the solar system with annual simulation calculations. At this stage the various collector technologies and their specific system costs can and should be investigated. When estimating the solar system costs, always take the effect of scale into account.
(l) Check whether the existing roof and/or façade surfaces are sufficient to implement a large part of the required driving heat with the solar thermal system. If it is possible and architectonically acceptable to integrate the collector system into the façade or on the façade, the collector system can serve a dual purpose – that is, for use to supply heat and as exterior shading. In this case, go back to point (d) and investigate its influence on the heating and cooling load.
(m) Produce a first cost estimate. For this, take the following information into account:
- Prices for electrical power (kilowatt-hour and capacity price).
- Prices for providing heat (kilowatt-hour and capacity price).
- Prices for the relevant collector technology. (Here the influence of the collector field size must be taken into account, as this can in some cases lead to very big price reductions. Thus, by enlarging the collector system from 10 m^2 to 100 m^2, in some circumstances it may be possible to reduce the specific system costs by around 30–50%.)
- Possible subsidies for the solar technology.

- Prices for the air-conditioning technology and cooling technology being considered. (Here bear in mind that, because of the intense competition in the air-conditioning industry, there may well be considerable price differences between the cost estimate and the results of the tendering process. This should be taken into account in the planning process.)

In general, the influence of the electrical capacity charge has a considerable influence on the cost-effectiveness of a thermally driven cooling system compared with an electrically powered compression chiller. However, in this respect it is critical to check whether the capacity peaks for the electrical power consumption are actually brought about by the air-conditioning task. If this is not the case, then this potential saving cannot be included in the economic efficiency evaluation. For future economic efficiency evaluations it may also be of interest to cash in on the possible carbon dioxide saving through emission trading.

After steps (a) to (m), iteration steps may still be necessary if the basic conditions in the planning process change. At first sight the process appears to require a lot of work, but the planning effort will pay off for the customer by providing a solution that is optimized in terms of energy and economics.

9.4 System technology

This section provides an overview of the system technology for solar air-conditioning systems. It will explain the fundamentally different concepts of autonomous solar-powered systems and solar-assisted systems. It will consider which collector technologies can be best implemented for the various thermally driven cooling technologies. In addition, it will describe various switching variants for the solar connection.

9.4.1 Autonomous solar-powered systems versus solar-assisted systems

In central European climates, autonomous solar thermal systems (related to the thermal power) are not economically viable as solar heating systems, because of the seasonally very different solar irradiance conditions. For solar cooling systems, on the other hand, two concepts are possible that are different not just technically but also in economic terms (Figure 9.9):

- solar-assisted systems
- autonomous solar-powered systems.

In *solar-assisted systems*, the solar energy supplies only part of the driving heat required for the summer air-conditioning. Whenever the directly available and/or

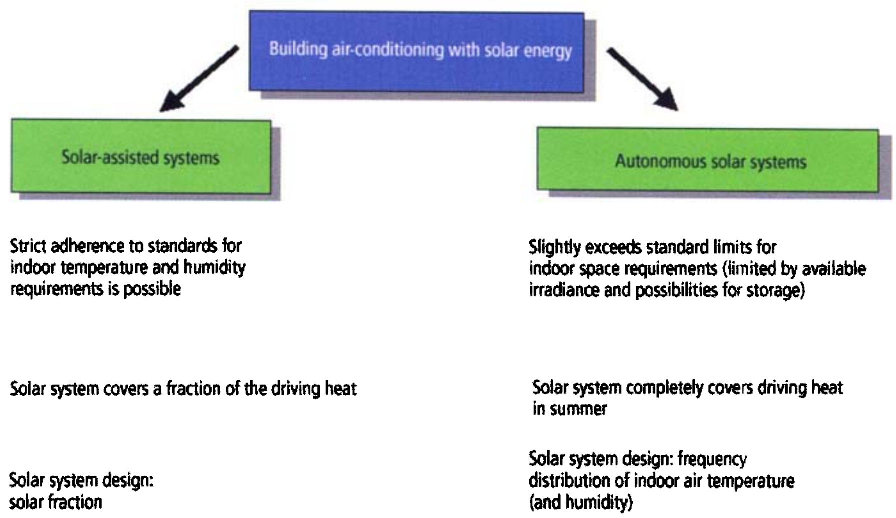


Figure 9.9. System concepts for solar cooling systems. Source: Fraunhofer ISE

Next Page

stored solar energy is insufficient, enough driving heat can be provided via the conventional auxiliary heating system. This enables the design requirements for indoor space always to be attained (if the cooling and air-conditioning systems are correctly designed). In these systems the attainable solar fraction is utilized for sizing the design. In this context, the solar fraction for cooling is used. This is always less than 100%. The solar fraction for heating can also be calculated based on the fraction of heat energy used for the heat supply and/or averaged for the heating and cooling season based on the entire energy used for the heat supply. The conventional auxiliary heating system is always necessary and is generally designed so that the complete driving heat can be provided via the auxiliary heating system. With detailed prior planning (simulation calculations of the entire plant are necessary), and depending on the building, climatic region and size of the selected heat storage tank, under certain circumstances it is possible to dispense with part of the thermal output from the conventional heating system. In this case, use of the solar system enables costs to be saved in terms of the auxiliary heating system. This can have a positive impact on the economic efficiency of the solar air-conditioning.

With *autonomous solar-powered systems*, the complete driving heat for the summer cooling and air-conditioning is provided by the solar collector field. In these systems, as much air-conditioning is achieved as possible with the available solar heat. An intelligent control strategy is very important in these systems. By their very definition, these systems dispense with an auxiliary heating system. The solar fraction for cooling is therefore always 100%. Thus it does not make any sense to design these systems using this parameter. As there is no auxiliary heating system in autonomous solar-powered systems, depending on the system design there may be hours with extreme external conditions when limit values for indoor temperatures and/or humidity are exceeded in the building. The number of these excess hours as well as the size of the deviations from the limit values can be determined through simulation calculations and utilized as design criteria. This is why, when designing autonomous solar-powered systems, it makes sense to use simulation calculations that consider the solar system *and* the building in *one* simulation. For buildings with a very large temporal correlation between the solar irradiance and the cooling load to be removed, self-contained solar systems are interesting not only technically but also economically. A typical example of such a building could be an office building used predominantly during the day with extensive glazed areas in the façades. The advantage of these systems lies in the simplified system technology. Costs can be saved by dispensing with the auxiliary heating system and the back-up heat exchangers. For autonomous solar-powered systems, integral planning is even more important, as changes in the building during the planning without a corresponding adaptation of the solar heating system can have an immediate impact on the later comfort conditions in the building.

9.4.2 Which collector technology for which cooling technology?

One of the most important questions concerning the system technology of solar air-conditioning systems is the choice of the correct solar collector technology.
To answer this question it is important to compare the driving temperatures of the various thermally driven cooling technologies. These are depicted in Table 9.2. The driving temperatures for single-stage absorption chillers are between 85°C and 110°C. For two-stage models they are even higher, at around 150°C. For adsorption technology the driving temperatures are somewhat lower at 55–90°C. The driving temperatures for desiccant cooling systems (DCS) are the lowest. This applies for desiccant cooling systems with both solid and liquid sorbents. With the latter, according to the current state of knowledge, the minimum driving temperatures are slightly higher (approximately 55°C); however, there is potential for improvement here.

Table 9.2. Overview of thermally driven cooling technologies and driving temperatures

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)
Driving temperature (°C)	85–110	55–90	45–90

10 Simulation programs for solar thermal systems

10.1 Introduction

Before a solar thermal system is built these days, a reputable planning office or installation company will first carry out a simulation of the system. Apart from the presentation of the results to the customer (marketing impact), this process is also increasingly being used to support the planning work.

Potential investors in or operators of solar systems ask for the optimum system solution, the expected solar yield and the level of energy saving. Simulation programs are essential to answer these questions. System planning should involve the optimization of the various system variants and system components on the basis of energy, economics and ecology. Whereas previously this optimization was possible only to a limited effect on the basis of empirical values, it is now made much easier – or even possible – with the aid of commercially available simulation programs. Nevertheless simulation does not replace draft design, estimation of the yield and reliable determination of the data that are necessary for planning. In order to obtain realistic results in the simulation and optimization of large or complex systems it is not only a powerful simulation program that is required but also the technical engineering knowledge of the planner. The results of a simulation are only as good as the realistic selection of the entry values and the simulation method. Many program makers have therefore begun to integrate plausibility controls at the data entry stage. This is helpful when gross dimensioning errors are made. Optimization can take place only if the planner knows which parameters or dimensions can improve the system to be planned, and if the program offers the optimization functions or variant comparisons. However, a critical evaluation of the simulation results is recommended for every planner because, in the end, the simulation program always assumes the optimum artificial conditions, which in reality cannot exist.

The time and cost savings in using simulation programs for dimensioning and planning have led to the increased use of these programs in planning offices. Installation companies are also increasingly using them for presentations to their customers. Some programs are particularly useful here because of the attractive graphics of the user interface. Determination of the yield, economic viability calculations and details of the saving in emissions show the advantages of solar systems, and supply sales arguments. Some programs combine the system layout, system data and results into a report that is ready for printing.

Some simulation programs are suitable for checking the calculations of existing systems if they permit the import of, for example, measured solar radiation and consumption data. These programs are indispensable during the daily handling of solar energy contracts or quotations. Which program is the most suitable for which application can generally be established according to the program classification, but it is finally up to the users to find this out for themselves by thoroughly examining the demonstration versions of the programs, readily found on the Internet.

Traditionally, in the areas of research and development or among the component manufacturers the various simulation programs have become indispensable. Increasingly, solar system component manufacturers are also offering programs that are tailor-made for their products.

10.2 Evaluation of simulation results

Solar thermal systems are used mainly in single-family houses as domestic water heating systems. Faulty forecasts due to simulation calculations are very rare in this area. However, if the systems are more complicated – for example a solar system that supports room heating, or a large solar system with several collector fields and buffer storage tanks – faulty forecasts are more serious.

For solar thermal systems it is essential to determine the planning bases, such as hot water consumption and heat requirements. If different consumptions or heat demands are found in practice, then the operating results will inevitably differ from the simulation results. Selection of the most suitable systems and components is also important, but it does not have such a significant influence on, for example, the solar yield.

The more complex the solar system, the more extensive are the input screens and the amount of input data required in the programs. Inexperienced users should make sure that they are clear about a parameter's significance before entering it. Most programs offer sensible guidelines for this purpose when the screens are opened. In spite of this, incorrect entries can never be fully excluded and this can lead to incorrect simulation results. The help functions also offer support here, although in some programs they could well be improved. A solar system can only be appreciably optimized by means of variation simulations if the user knows what effect any 'tweaking' will have.

The results should always be checked on the basis of empirical values. A solar system with a specific yield of below 250 kWh/m²a is in general incorrectly designed. Even with good results, for example a specific yield of over 600 kWh/m²a, there should be critical consideration.

10.3 Simulation with shading

The number of simulation programs with an integrated shading editor is constantly increasing. Programs that did not have this facility in older versions have integrated an additional calculation option for shaded systems during version updates.

Unlike photovoltaic systems, partial shading of the receiving surface at certain times of the day or year is less serious for the yield in the case of solar thermal systems. Collectors are much more able to convert diffused radiation into useful energy too. In addition, shading presents no risk for the safety of the system operation.

If the shading losses are known, the resulting losses in yield can mostly be compensated for by increasing the area of the collector surface. The degrees of utilization are naturally somewhat lower, but the desired system yield can be achieved at relatively little additional financial cost.

With the aid of comparative calculations the user or customer can be shown the effect of, say, a 20-year-old birch tree on the system yield, and this can help to eliminate the misconception that a solar system cannot be installed without felling the trees in the front garden.

10.4 Market survey, classification and selection of simulation programs

There are multiple applications for solar energy, and so there are also as many simulation programs. No matter whether it is used for domestic water heating, room heating support, swimming pool heating or solar air systems, any solar thermal system can be simulated on a computer. However, most programs are concerned with solar domestic water heating and room heating support. To summarize the market, the simulation programs can be classified according to their programming process into

- calculation programs
- time step programs
- simulation systems
- tools or auxiliary programs.

The simulation approach used in the program determines the accuracy, operating effort, flexibility, scope of application and calculating time, although the latter is now less significant because of the greatly enhanced performance of modern computers. These properties increase as we move from simple calculation programs to dynamic simulation systems: the more flexibly a program can be used, the greater the demands it places on the user.

The final category contains programs with sensible additions, specifications for detailed problems or for the design of the individual components of solar systems. For the selection of a simulation program, apart from the simulation process itself, the application is naturally also important. This brings in the question of the performance and the application options for the program. Therefore the system type or system configuration for which a simulation is required is important.

10.5 Brief description of simulation programs

In the following a selection of the most widespread simulation programs for solar thermal systems is introduced. For many programs a free demonstration version can be requested or downloaded via the Internet. Also, several manufacturers supply simulation software for their products: some of this has worldwide application.

10.5.1 Calculation programs

Calculation programs are simple programs based on static calculation processes. Usually it is only the average monthly values that are included for the individual locations. On the basis of the alignment, the collector type, the size of the collector surface area and the hot water consumption, they determine the yield for the whole system. They deliver quick results, mainly in the area of standard systems for domestic water heating. The behaviour of a system under specific conditions and at smaller time intervals cannot be considered. Also, the various system configurations available on the market can only be reproduced in a very restricted way.

10.5.1.1 F-CHART

The well-known and widespread calculation program f-Chart offers a simple-to-operate user interface for dimensioning a solar thermal system for domestic water heating with a solar storage tank. The entries are made via a screen, which is arranged for meaningful entry values from the start of the simulation. The help function also includes advice on the limits and size of the parameters to be entered. About 100 European weather data records are integrated into the program (monthly averages) together with 98 collector data records.

The accuracy of the f-Chart process with respect to the result of an annual simulation is sufficient even in comparison with time step programs. The degree of solar coverage, and the energy and emission savings, are output as monthly averages over the year in the form of graphics or tables in a three-page report.

Because of its clear layout and user friendliness it is recommended for installation firms, energy consultants and craftsmen, as such people often handle orders for standard systems for domestic water heating in one- and two-family homes.

More information and a demo version can be found at www.fchart.com

10.5.2 Time step analysis programs

Whereas calculation programs only carry out static simulations with monthly values, time step simulation programs permit a more dynamic evaluation in a particular time cycle. Simulation takes place on the basis of weather data and consumption values in an hourly or shorter resolution. Some programs permit instantaneous displays and for example the determination of storage temperature at a given time. The user selects the appropriate system type from preset types and the corresponding collector from the collector library, and enters the parameters for the system location and further system components.

The program user interfaces are arranged to be user friendly. Experienced Windows users will not require a lengthy familiarization period.

10.5.2.1 T*SOL

Since the beginning of 2001 the popular program T*SOL has been available in a fully revised 32-bit version. This fundamental revision of the extremely successful program took account of the increasing demands that are placed on time step analysis programs. T*SOL 4.0 is available in one variant (professional), which is described below. In the near future an expert's version should also be available.

The professional version replaces the previous version 3.2, and essentially retains all the previous useful functions. T*SOL program is popular because it can perform simulations over any time period. The temperatures can be observed during the simulation by means of a coloured display. The results (temperatures, energies, degree of coverage and utilization) can be output at a resolution as short as one hour as tables or graphics. An easy-to-use viability and emission calculation is integrated. A helpful feature has been found to be the simple copying function and the export/import of consumption and results data for accurate analysis in other programs (for example in table calculation programs).

Furthermore additional system variations are possible in version 4.0, which result from the integration of further libraries. Apart from the well-known collector and location libraries, a storage tank and heating boiler library is also integrated for the first time into a simulation program. As well as domestic water and buffer storage tanks, combined storage tanks (tank-in-tank systems) are now also included. Therefore it is now possible to simulate such systems with accurate product data as measured at the manufacturers' premises. Free configuration as in simulation environments is not possible, however, as otherwise the user would have to first compile a newly created system, but it is possible to reproduce individual company-specific systems that differ from the preset program options (see also Figure 10.1).

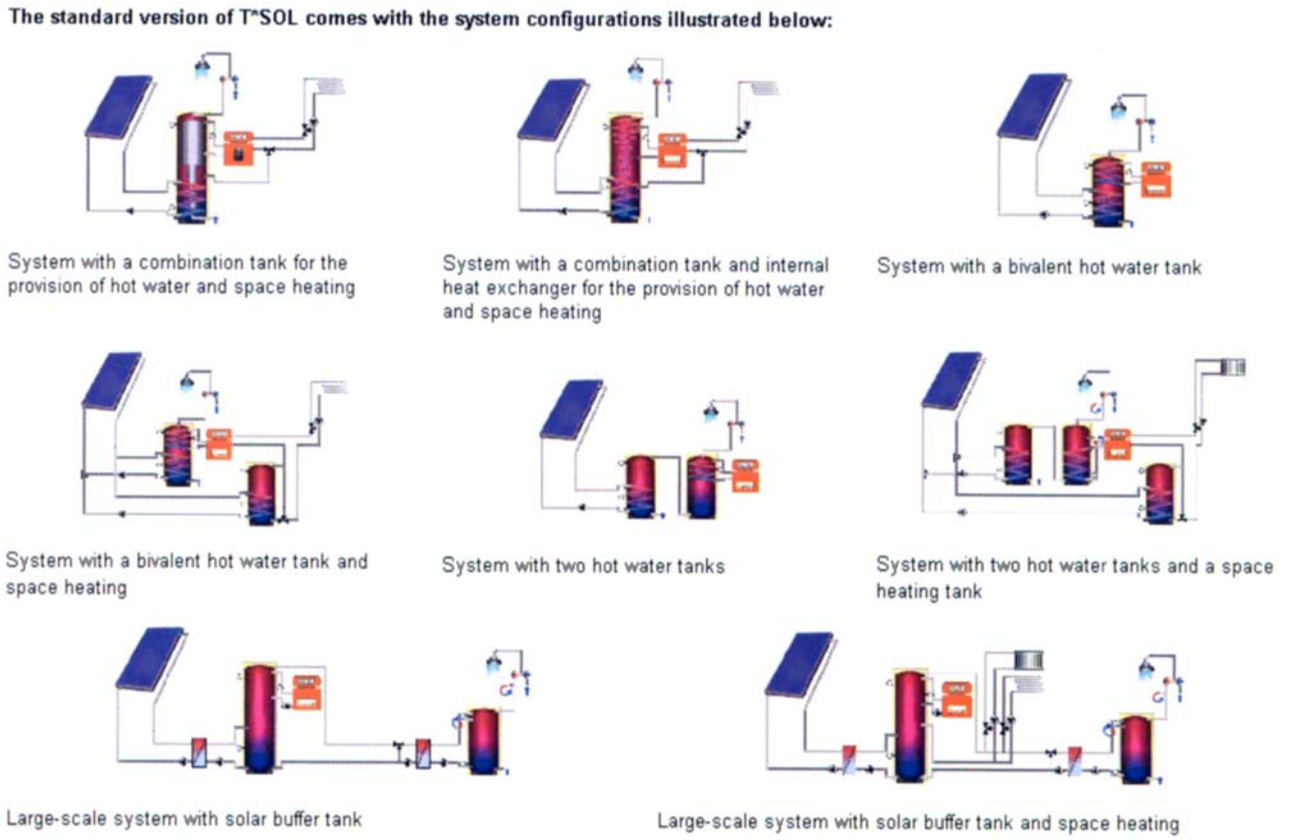


*Figure 10.1. System configurations supported in the standard versions of T*Sol (source: www.tsol.de).*

The suppliers of such systems can then distribute this as desired (for example ready to download from the Internet) and hence make them available to the planners or installers. The program supplier Dr Valentin GbR has even taken the step of carrying out product support and updates, for example also for collector and storage types, mainly via the Internet: http://www.tsol.de/.

As in the previous version, numerous collectors' and weather data are included in the program. It is also possible to continue to procure additional weather data for outside Europe from the manufacturer or to import it using the METEONORM program (see section 10.5.4.2).

For better calculation of systems that support room heating, a single-zone model for thermal building simulation is also now integrated into the program.

Additional new tools for the professional version of T*SOL 4.0 are a shading editor and a design assistant. This permits draft designs to be produced for different degrees of coverage, and also carries out rapid simulations for three possible variants. The results can be shown in two different project reports. Visualization of the results and the simulation itself have also been improved: for example, it is now possible to observe how the layers of a solar storage tank function during the simulation.

Simulation of swimming pools (both indoor and outdoor) can be carried out with a supplementary module in the same way as for version 3.2. A further supplementary module, SysCat, permits the calculation of large solar systems.

In the expert version there will be multiple variation and simulation options for the scientific user. Measured values for radiation and water consumption can be imported with an hourly resolution, and for experimental simulation all the characteristic data for collectors and storage tanks can be changed.

Further plans are being made to simulate different alignments of collector fields, to dimension the expansion vessel, and to optimize the design of the pump. Through the modular construction of the program these options should be capable of integration into the existing program with no problems.

T*SOL is available in different languages (English, German, Italian, Spanish and French); more information can be found at http://www.tsol.de/englisch/startseite-e.htm.

10.5.2.2 POLYSUN

The Swiss Windows program Polysun is comparable to T*SOL in its scope of performance.

The weather data from more than 300 European locations are integrated into the program with an hourly resolution (Figure 10.2). Eleven different system variants, including one with a combined storage tank, can be selected. Version 3.3, which has been available since December 2000, is able to simulate large tanks better. Here the problem often arises that, at the start of the simulation, an unrealistic situation takes place in the storage tank. If the conditions in the storage tank differ by more than 5% from the starting values after the year's sequence has been completed another annual simulation is automatically appended.

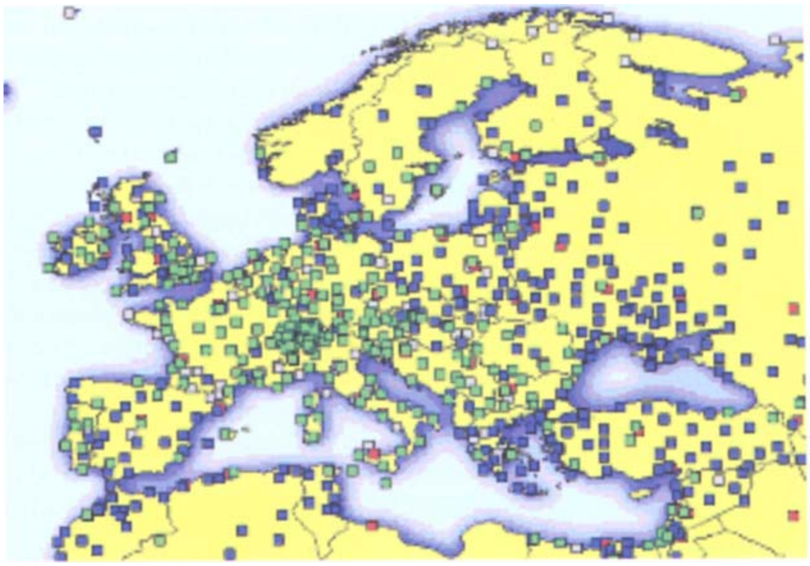


Figure 10.2. Meteorological sites available in Polysun

The integrated collector library from SPF Rapperswil now includes over 170 types of collector, whose measurements took place according to the new EN/ISO standard. Updates can be obtained from the respective sales offices or on the Internet (http://www.spf.ch/). The hot water consumption can be edited in the same way as in T*SOL, but in a somewhat more restricted fashion. Four types of typical daily profile can be selected. Holidays, which are periods in which no hot water is needed, can on the other hand be freely selected. An instantaneous value display of the simulation is not possible with Polysun. The simulation time is relatively short. The release times of the boiler and the circulation circuit can be given in an hourly resolution. The inlet or connecting heights of the stratified storage tank, the auxiliary heating and the temperature sensor can all be individually set.

The program has a cursor-controlled shading editor and a thermal building simulator with a database of 20 examples of building types.

The waste pump heat can be defined as a percentage, just as for the glycol portion in the heat transfer medium. In addition, the latest version of the program supports the optimum selection of the pump by calculating the pressure loss of the solar circuit on the basis of data given in the program using the auxiliary program TubeCalc.

The output of system data and the results (energies, degree of coverage, economic viability balance etc.) is in the form of a presentation, detail or engineer's report. An expansion for version 3.3 is the calculation of emission savings, which, as for other programs, can also be output as an ecological balance. In this case the savings are considered with respect to the eight most important greenhouse gases. The economic viability dialogue is saved with the variant so that a cost optimization can be made quickly and simply. Country-specific figures for energy prices, interest rates etc. can be separately edited. Dimensioning help for the user has also been expanded, for example by fully revised help texts.

Temperature sequences, for example in the storage tank, cannot be displayed either in the program or in the results. Another disadvantage is that the results can be issued only as monthly values.

The target groups for the program are installation companies, engineering and planning offices, and training and education institutions. The program can be obtained in German, English and French. The languages can be switched over on-line so that processing can take place in the mother tongue of the planner but, if necessary, the report can be printed in the customer's own language.

10.5.2.3 GETSOLAR

The GetSolar program for the simulation of solar thermal systems, well known as a DOS program, has been available since 2000 in a Windows version. At present version 6.1 is available. The first version change after the step from DOS to Windows permitted the simulation of six different system variants. Added to this is now the combined tank (tank-in-tank). Apart from the existing weather data for various locations, the METEONORM data sets can also be imported. A time loop function permits detailed system observation at critical moments. The program errors in the first Windows version have been corrected.

GetSolar carries out fast simulation of solar collector systems, and the excess heat for solar room heating support can also be calculated if desired. Among other things it contains a library of the data for 120 collectors and a shading editor. Calculation of the sun's level, insolation, yield, degree of coverage and utilization is possible in various time resolutions. Instantaneous values can be shown. The results can be copied into intermediate storage and then processed in other programs. Special features are the design of the expansion vessel, calculation of the collector stagnation temperature, consideration of single or twin-axis tracking, and various inclinations of the absorbers of evacuated tube collectors. The consumption profile can be defined for a standard day.

The program cannot carry out economic viability and emission calculations. However, it is certainly of interest because of its attractive price and respectable simulation results. The program is in German but can be switched to an English-language interface.

10.5.2.4 RETSCREEN

Developed in Canada, RETScreen is a standardized renewable energy project analysis program that will help in identifying and evaluating the most viable opportunities for cost-effective implementation of renewable energy technologies (Figure 10.3). RETScreen uses MS Excel spreadsheets to provide pre-feasibility studies for a fraction of the time and money required by conventional methods. The software can be downloaded free of charge at http://retscreen.gc.ca

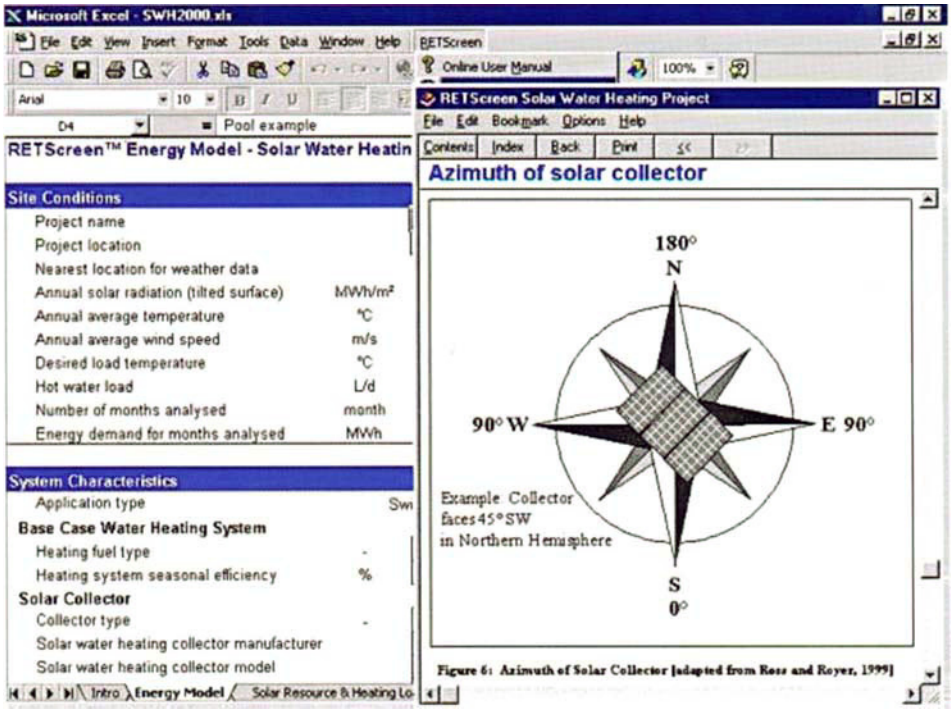


Figure 10.3.
Screenshot of RETScreen software

10.5.2.5 FRESA

The US Federal Renewable Energy Screening Assistant (FRESA) Version 2.5 allows energy auditors in the DOE SAVEnergy Program to quickly evaluate renewable energy opportunities and energy systems options for possible inclusion in a facility's energy program. More information can be found on http://www.eere.energy.gov/femp/techassist/softwaretools/softwaretools.html#fresa

10.5.3 Simulation systems

When the limits of time step programs and their relatively rigid user interface are reached – as in the case of larger solar systems with more than 100 m² surface area or more complex systems – the use of dynamic simulation systems becomes necessary. Because of their flexibility, almost any sort of system configuration and operating condition can be simulated. This versatility, however, is accompanied by greater demands on the user. Longer familiarization times (months) must be expected for these simulation systems. The programs permit the solution of relevant differential equations, often contain a multi-zone building model, and can be used in the case of the complex relationship between heating, and active and passive ventilation or cooling.

10.5.3.1 TRNSYS

The Windows program TRNSYS is surely the classic and market leader among simulation systems (Figure 10.4). The most varied thermal building and technical energy system simulations can be carried out with this program. The flexibility and the numerous predefined systems and standard components are the main features of the program. TRNSYS is a common simulation program that was developed in 1974 at the solar energy laboratory of the University of Wisconsin, Madison, USA. The program language is English or French. The program has a graphic user interface and diverse results presentations. Interfaces to other programs (CAD and various simulation programs) are also provided. For the experienced computer user the source code (Fortran and C++) of the program can be edited, and the mathematical description is accessible. Apart from superior computer capabilities the user should also be knowledgeable in the area of solar structures and system technology and have a deep understanding of simulation models. A basic knowledge of programming is useful; without it users will have difficulties in familiarizing themselves with the program.

Its use with many completed buildings has proved the performance and accuracy of TRNSYS simulations. The target groups for the program are larger planning offices

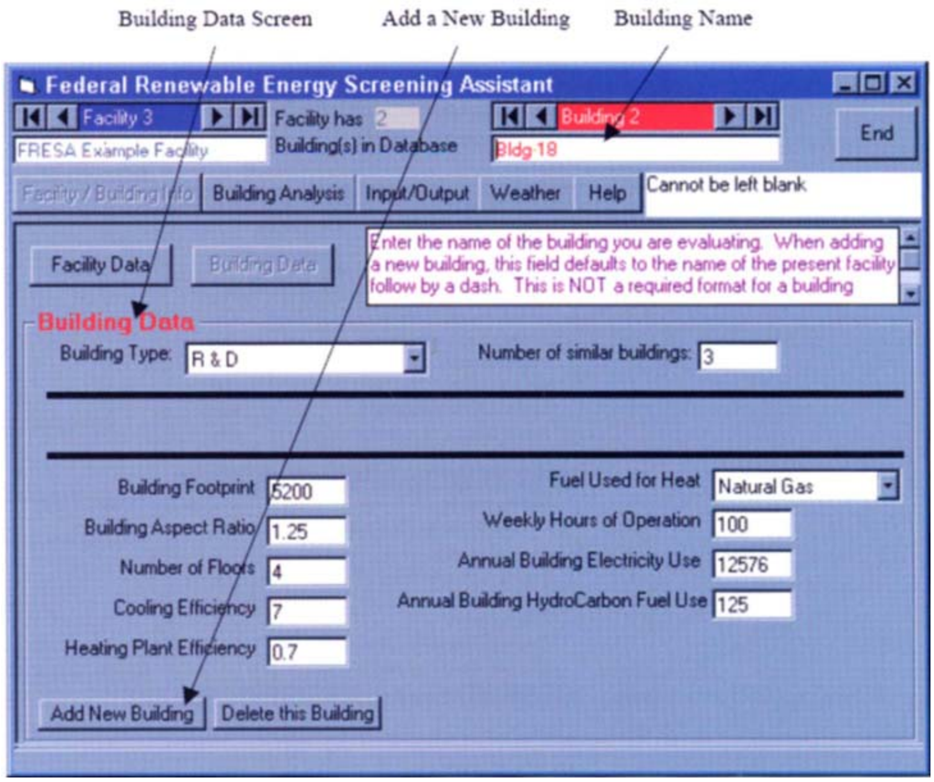


Figure 10.4.
Screenshot of FRESA software

and firms specializing in building and system simulation. TRNSYS is also used extensively in universities and colleges and for research and development. In the area of solar thermal systems the various types of collector are prefabricated and can then be parameterized. Certain solar system examples are also included in the standard package. Thus for example thermosyphon systems, various heat exchangers (counter, parallel flow and cross-flow etc.), concentrating collectors, stratified and stone-filled storage tanks can all be simulated.

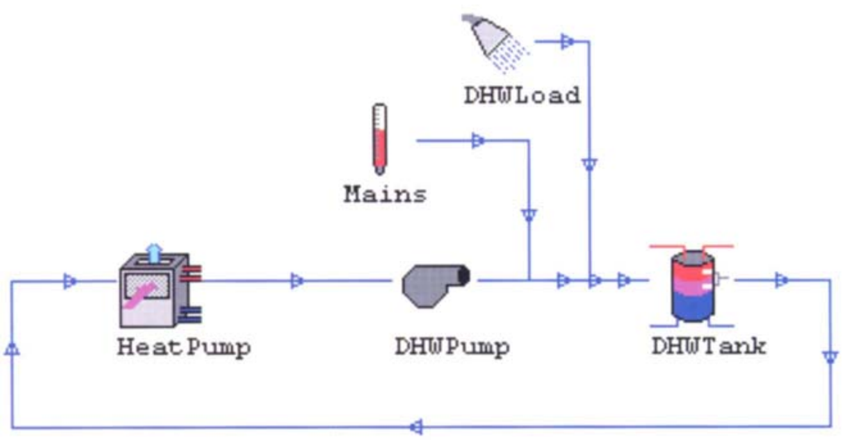


Figure 10.5.
Screenshot of TRNSYS software

10.5.3.2 SMILE

SMILE is a simulation environment developed by the Technical University of Berlin and the GMD (Society for Mathematics and Data Processing). It provides an object-oriented programming language for describing models and computer experiments as well as all the component parts required for all simulations. The applications are mainly in the energy area and extend from solar thermal systems, photovoltaic, heating and air-conditioning technology, hydraulic networks via building simulation to power station technology. The particular strength of SMILE is its ability to combine all these applications by means of integrated examination.

SMILE has proved its capabilities in the university area in various research projects over a number of years. This scientific origin is evident when SMILE is used: thus a graphical user surface that is also appropriate for occasional users is only now being developed). It is certainly an attraction that the program can be procured free for non-commercial use. To date the program has only run on various UNIX platforms such as LINUX.

For special applications, such as building simulations, graphical user surfaces and visualization tools already exist. In a current research project the linkage of CAD architecture software to thermal building simulation has been realized in SMILE in order to be able to carry out energy analyses for geometrically complex buildings within a reasonable time. Also visualization has been integrated in the area of pipe network simulations, such as local area solar heating networks, which permits the simulated pipe network to be closely examined. In the meantime the user has been offered through the support of the SMILE home page by the TU Berlin a reference manual, a tutorial and an expanded component library. Commercial licences can be obtained for SMILE from the firm Dezentral GbR (at www.dezentral.de). Here complete support can be obtained, the program can be optimally set up, and an introduction to the program is possible in user training courses. Dezentral also supplies SMILE solutions for special applications that conceal the complexity of the system from the user by appropriate user interfaces.

10.5.4 Tools and help programs

Numerous small help programs (tools), which as well as the simulation programs also provide supplementary help for daily work in the area of solar energy, are available. A few programs are described in more detail in the following.

10.5.4.1 SUNDI

The Windows program SUNDI is a simple-to-operate program for shade analysis. On the screen it is possible to represent sun-path diagrams throughout the world with the shading as entered and hence determine the times at which the shade occurs. Furthermore the irradiation losses as a result of shade can be calculated and issued. The SUNDI program can be procured free over the Internet. SUNDI is a sensible means of supplementing programs that do not have integrated shade editors, such as f-Chart.

More complex statements can also be made on shading, and finally the results can be easily copied and used in other programs, such as PV simulation programs or thermal building simulations.

10.5.4.2 METEONORM

This well-known Windows program contains a worldwide weather database (with 626 weather stations and 359 towns) and a weather generator. It calculates the hourly values of insolation and interpolates the horizontal global radiation and the temperature of every location in the world. In addition further climatic data such as air humidity, dew-point temperature, air pressure, wind direction and speed can be issued as hourly values. METEONORM contains worldwide sun-path diagrams and can convert the global solar irradiance for inclined surfaces. A shade editor permits horizontal shading to be taken into account. The results can be read into various programs. More info can be found on http://www.meteotest.ch/en/mn_home?w=ber

11 Marketing and promotion

11.1 The fundamentals of solar marketing

11.1.1 Customer orientation: the central theme

What actually *is* marketing? We like this definition best:

> *Marketing is the totality of the measures that make it easy for your customer to choose you and your product.*

We have divided the subject into three parts: the fundamentals, systematic marketing planning, and the sales discussion – the most direct form of contact with the customer.

Solar energy is an attractive energy. It represents the future and a respectful attitude to the natural and the human environment. In selling a collector you are partly selling this idea. Customer benefit should be the main theme of your marketing strategy.

As the reader you are our customer. What therefore is the benefit of this chapter to you? More enjoyment in sales and acquisition – and more success with less effort. The additional success you will have is shown in the following:

WHAT WILL YOU GET OUT OF SELLING SOLAR SYSTEMS?

You will be:

- Promoting something good (of benefit to the environment and society and of benefit to you as well).
- Advising your customers (your customers' benefit is your benefit).
- Strengthening customer relationships (paving the way for further sales, increasing the level of familiarity).
- Gaining in competence (practice makes perfect, technically and consultatively).
- Improving your image (at the very least showing the customer that you have their welfare at heart).
- Gaining personal satisfaction (emotional self-interest).
- Safeguarding workplaces (safeguarding your own workplace, future opportunities).
- Adding value.

11.1.2 The iceberg principle

Just as you only see one seventh of the volume of an iceberg, similarly only one seventh of our communication is conscious; by far the greater part is invisible (Figure 11.1). However, this part determines the behaviour and the decisions of the person to

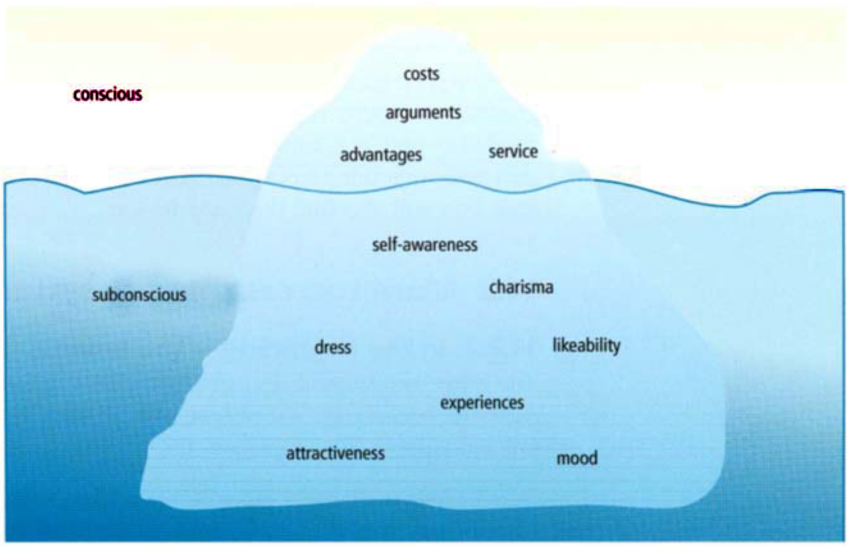


Figure 11.1.
Only one seventh of communication is conscious

whom you are talking. This is true even when trust and a long-term customer relationship with mutual benefit is involved.

This means that, to obtain new business, you must deliberately plan using your common sense. For continuing success, however, your attitude, your feelings and the feelings of your customer are important. It is also important how you dress, and how you behave. You are not only selling a product, you are also selling what you 'represent' as a person. Are you credible? Are you good company? Do you have a good rapport with the customers?

The iceberg principle also means that a customer notices very quickly whether you are genuine – for example whether you are really interested in what *they* want. It is therefore worth considering fundamental questions such as: What is the aim of your work? What impression do you want to leave with your customers?

11.1.3 The 'pull' concept

He or she who wishes to sell more, first feels a pressure to be rid of something. According to the iceberg principle this pressure is transferred to the customers. They react in the same way that you react to pressure – with resistance! It is much better if you can see yourself as the answer to your customer's prayers. You read the desires of your customers and can provide all sorts of good products and services for their benefit. In this way you build up a 'pull', which attracts the person you are talking to.

Customers will buy something because they are convinced of its benefit. Attitudes and feelings play an especially important role in the pull concept. In addition to the factual information that you provide, they convey an image of your company and your product. You will acquire business if you can portray your product and company so attractively that your customers want to buy exclusively from you.

The most important differences between push and pull are listed in Table 11.1.

Table 11.1. The difference between push and pull (according to Binder-Kissel[2])

Push	Pull
Use every discussion to 'grab' potential customers Aggressive selling Sale at any price	First build up trust through general discussion, identifying the starting points for cooperation Sale only if the customer really wants something
One discussion = one completion	Honest, serious advice Acceptance of a 'no'
Company image, second priority	Image as significant factor → attractiveness for potential customer
Completion = success factor	Word-of-mouth recommendation A recommendation to somebody else is also a success
→ Critical customers, who were forced into buying High complaints rate Price sensitivity	→ Satisfied customers, who come by free will Fewer complaints Lower price sensitivity

Modern marketing operates according to the pull concept. As the differences between the products of competitors become smaller, so the significance of the relationship between company and customer becomes more important. Marketing therefore does not stop with the sale but sees it as the beginning of a new sale. That may be another product or another customer. What is most important is your behaviour when you create the pull. Is it enjoyable to work with you, to recommend you to others, to purchase something from you? If you make it easy for customers to see the benefits then they will also find their way to you.

11.2 More success through systematic marketing

11.2.1 In the beginning is the benefit

You know and respect your product from a salesman's point of view. However, each customer sees it from a different point of view. It all depends on perspective! The following shows how important this is:

> A novice said to an older monk: 'I have noticed that you smoke during your prayers. The abbot has forbidden me from smoking during prayers.' To this

the older man replied: 'It all depends how you approach the abbot: I asked if I could pray while I was smoking.'

The customer is not interested in the fact that a solar thermal system is 6.6 m^2 in area and has a selective coating with an emission coefficient of 5%. What he or she wants to know is whether it will supply hot water between April and October. Craftsmen and engineers often concentrate on the technical data as the significant features of their product. Customers, however, are mainly interested in what they will get from it – this is often different for men and women, as it is for private individuals and industrial customers.

Take a look at your products and services and gather together the customer benefits (Table 11.2 shows some examples). Note that there are several benefits to each feature. Identify all the possible benefits from the customer's point of view. The following list of potential benefits will help you in your detective work:

- time saving
- solution to a problem
- cost saving
- environmental protection
- security
- prestige
- enjoyment
- comfort
- health
- information
- entertainment
- public relations (for business customers)
- motivation of staff (for business customers).

Table 11.2. From features to benefits

Feature	Advantage	Benefit (for customer)
Tempered glass	Resistance to hail	Long service life, no troubles and no repair costs
In-roof installation of collector	Better thermal insulation	Fuel cost savings Visually attractive through harmonic integration into the roof skin
22 m^2 collector system	Higher thermal yield	Low fuel costs Noticeable use of the sun even in winter Secure supply in emergencies Reduction in cost risk when energy prices rise
800 l storage tank	Large storage capacity	Hot water reserves in times of high consumption Better utilization of high irradiation Longer bridging of poor weather periods
Storage tank with flow heater principle	Hygiene	Fresh, healthy domestic hot water

11.2.2 The four pillars of the marketing concept

Tie your new business development and sales efforts into a marketing concept. Instead of random calls, cultivate the market systematically. Even two days spent on concentrated planning will save you lots of time, money and stress in the future. You will be able to target your efforts and fill the gaps in your sales cycle; turnover will increase and will continue to do so.

Such a marketing concept is supported by four pillars: analysis of your company, your products, the market and your marketing turnover. In this chapter we are concerned mainly with the last two points. However, it is worth examining the other two areas, and some suggestions in the form of questions are given below.

11.2.2.1 THE COMPANY

WHAT ARE YOUR OWN OBJECTIVES IN YOUR WORK? WHAT IS IMPORTANT TO YOU?

In marketing, your aim should be to acquire orders that serve your own objectives. Your concept of yourself is also important here: for example, do you want to sell as cheaply as possible, or is quality the most important aspect? How important to you

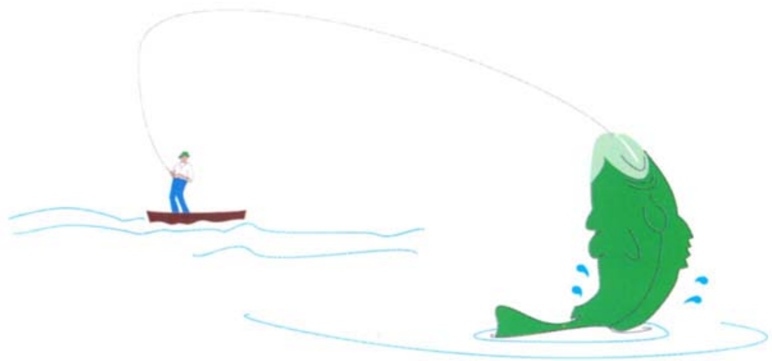


Figure 11.2.
The bait must be tasty for the fish, not the fisherman!

are ecological and social concerns? Are you happy with the external image of your company?

WHAT CAN YOU OR YOUR COMPANY DO PARTICULARLY WELL (STRENGTHS)?

Are you a person who likes fiddly jobs and enjoys designing complicated systems? Or can you handle large-scale standard projects particularly well? The more you concentrate on your core competences the more readily you will be recognizable externally. Customers can then classify you more easily: 'the specialist for heating support from the sun'.

WHAT ARE YOUR OR YOUR COMPANY'S WEAKNESSES?

How does your after-sales service system operate? How long does it take to answer a customer enquiry? Are your most important members of staff – those who are customer-facing – properly trained? You should also consider resources with respect to your marketing. If your efforts were to be successful, could you deal with all the orders and still meet customer expectations?

11.2.2.2 THE PRODUCTS

WHAT ARE THE MOST IMPORTANT BENEFITS THAT YOU OFFER YOUR CUSTOMERS (STRENGTHS)?

This includes both your services (quality, planning services) and equipment (collectors, boilers etc.). Are you up to date? Have you got suitable products for your target group?

WHAT WEAKNESSES DOES YOUR PRODUCT HAVE IN COMPARISON WITH THE COMPETITION?

What reasons do interested parties give for deciding against your offer? What complaints do you get from past customers? Perhaps in the medium term you could include an alternative product in your range, or you could balance, for example, a higher price with extra services such as a free check after one year.

FROM WHICH PRODUCT DO YOU EARN THE MOST? WHAT GIVES YOU THE MOST PLEASURE?

These questions can have consequences for your marketing, your calculations, or the general aims of your company.

11.2.2.3 THE MARKET

WHO ARE YOUR COMPETITORS?

In which area do you work and what are your target groups? What is your reputation, your price structure? How big, how aggressive are you? It is a good idea if now and again you can have exchanges with your competitors, perhaps even carry out common campaigns. If you select your target groups carefully you will generally get on well alongside each other.

WHAT IS SPECIAL ABOUT YOUR OFFER WHICH MARKS IT OUT FROM THE COMPETITION (POSITIONING)?

Formulate this in one or two sentences:

> We are specialists for pellet heating with solar involvement. Our firm includes roofers and heating engineers.

You can use this both in printed leaflets and at exhibitions in order to introduce yourself to interested parties. In this way you will be better remembered. Pay particular attention to your positioning. Price, service, quality – all appear equal in one sense. However, customers may be persuaded to opt for your system if, for example, you have an attractive display that graphically shows the solar gain.

WHO ARE YOUR TARGET GROUPS?

Whose problems can you solve best? Who is most likely to be persuaded by the benefits you are offering? (See Figure 11.3.)

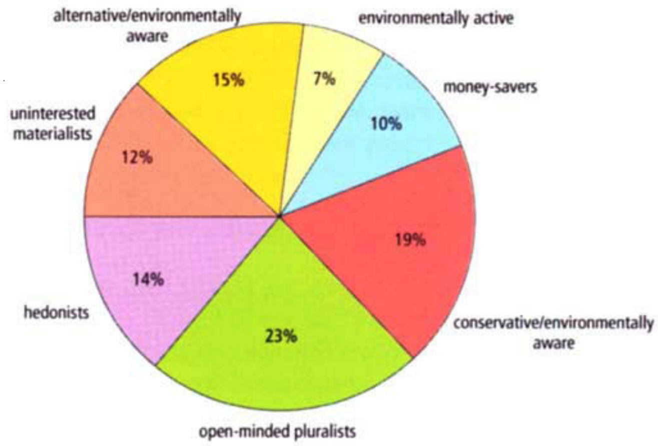


Figure 11.3. Values and consumption patterns of households asked about saving energy Source: Prose & Wortmann (1991)[53]

You can develop a separate acquisition strategy for each group. So, for example, alternative/environmentally aware, environmentally active, and conservative/environmentally aware can be targeted with ecological benefits – however, each of the three groups has a different attitude towards life. Correspondingly important are the peripheral elements of your marketing, such as your dress and appearance. This is particularly evident in personal discussions. It is sensible for each person to accurately seek out and talk to his or her target group(s).

MARKETING TIP

Working with schools, you could offer a day of orientation for school leavers. In this way you could ensure new 'solar recruits' and at the same time reach two multiplier groups: pupils and teachers.

With the watering can principle (Figure 11.4) you will never be able to penetrate through the general mass of advertising. It is only with a 'targeted stream' that you can achieve the necessary intensity. And with a targeted stream you can maintain this intensity, as you are only trying to reach a restricted group.

Figure 11.4. Target group derives from target. You won't get rich with the watering can

In your examination of target groups, start with your own experiences. What moves people? Which groups do you feel will be the ones that respond? They may expect that you too should 'take a risk'. Seek opinions from uninvolved people, laypersons, acquaintances; exchange thoughts with your colleagues; survey your customers; read specialist magazines and your local newspaper.

In this way you can keep your ear to the ground and stay aware of what is going on. Perhaps a new building area is being planned, or a solar initiative is being formed in your community.

MARKETING TIP

In a new building development you could make yourself known by direct mail or a mailshot. Those who build do not usually have the money for additional things such as solar systems. You could play along with this and say:

> We can offer you non-binding advice as to how you can prepare now for the installation of a solar system at a later date at very little cost.

The threshold for such a customer to make contact with you is thus very low, as there is no need to invest anything at present. He or she will remember you, however, when the need for a solar system eventually arises. And you also offer services other than solar energy; perhaps the customer is unsatisfied with a sanitary installer, and if you are already known...

11.2.2.4 MARKETING TURNOVER

WHO DOES THE MARKETING IN YOUR COMPANY?

The best answer to this is – everybody! From the telephone operators to the customer service technicians, all employees should know how they can contribute to gaining and keeping customers. Are the external sales staff motivated? Is there a training need?

WHAT MARKETING RESOURCES DO YOU HAVE?

These resources extend from printed matter, brochures and sample letters up to standardized procedures. How do I carry out a complaints discussion? How do I behave on the telephone? How is an enquiry dealt with?

WHAT SORT OF MARKETING EXPERIENCES HAVE YOU HAD TO DATE?

Evaluate this in terms of time, money and enjoyment on the one hand and success on the other. Have there been unexpected effects that you can build on and use? What have you not tried yet?

Don't be satisfied with easy answers. If, for example, you were not satisfied with the results from an exhibition, ask yourself: 'Was this due to the exhibition itself or was this my fault?' Are there other exhibitions through which you could reach your target audience better? How can you prepare better? Did you do everything possible to interest the target group?

STRATEGIC CONSIDERATIONS: THE 7C STRATEGY

Before you study the range of marketing tools in more detail, we would like to introduce you to the 7C strategy (C = contacts). This is the basis for the targeted selection of marketing tools. The selection creates a marketing concept out of random marketing.

Figure 11.5 shows the phases involved in winning customers. Without regular reminders, customers will forget who you are – conduct regular campaigns to create interest and refresh their memories! This 'pre-sales' phase requires mental staying power; as soon as you detect some interest it becomes easier.

As a rule of thumb you need seven contacts to gain each new customer. This can extend over years. Do not be put off; the first contact hardly ever leads to success.

In the next section important marketing tools will be introduced. On the one hand the selection of an advertising medium depends on the target group and the message, but it also depends on the advertising budget. Be aware of the difference between fixed costs (for advertising) and variable costs (for example postage costs for mailshots), but also be aware that production costs can vary enormously. For example,

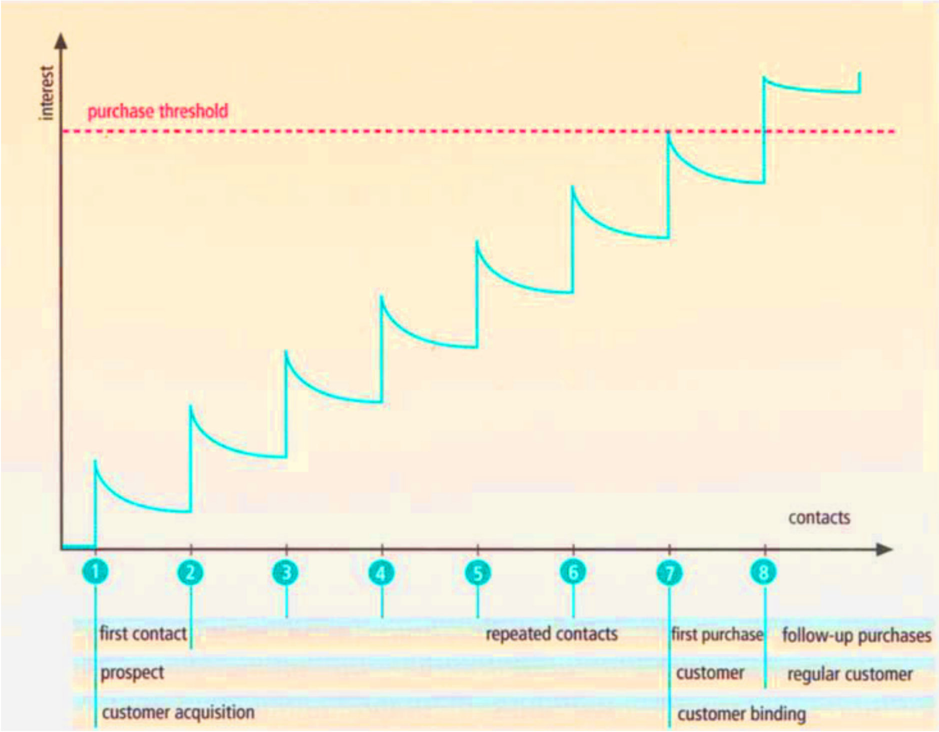


Figure 11.5.
The phases of winning customers according to Wittbrodt[64]

the production of printed advertising material is only a fraction of the total production cost for television advertising.

THE COVERAGE OF MARKETING

This list is ordered according to coverage achieved. At the same time, as you move down the list, the mode of address changes from the direct (personal) to the indirect (for example displays), and the absolute costs (not the cost per contact) increase.

- personal contact
- telephone
- event
- mailshot
- newspaper, TV, radio.

Rule of thumb: The smaller the target group the more direct the approach.

11.2.3 The range of marketing options

11.2.3.1 DIRECT MARKETING

PERSONAL CONTACT

The iceberg principle (section 11.1.2) becomes evident with personal contact. Here you can use your personality to build confidence and create a personal bond. Personal contact is mostly used to convey comprehensive advice to interested parties, and is the preparation for final agreement in a sales discussion. It is dealt with in detail in section 11.4.

TELEPHONE

The telephone is an intensive form of personal contact in which all components of the iceberg play a part. With the telephone you create a personal closeness to the customer. You can hear the 'undertones'. How genuine is the interest? Is it an anxious customer who needs security? Or is the customer well informed, and just in need of clear facts? The telephone is ideal for helping hesitant interested parties over the contact threshold to the next stage.

As a rule, with the telephone you can pick up early expressions of interest which you can then supplement with a mailshot. Telephoning is an art that you and your staff can learn. Section 11.4 provides some suggestions; it is worthwhile pursuing this theme more intensively

MAILSHOTS

Mailshots are the most commonly used marketing tool, which is why they are given more space here. They are a good compromise between the direct and indirect approaches, and stay within reasonable financial boundaries. You can use mailshots for various purposes:

- to create interest – for example to create an initial contact
- to update wide target groups (offers, events, new products), for example within the scope of the 7C strategy (see section 11.2.2.4)
- as regular reminders in order to build customer relationships.

In general mailshots should trigger a reaction and the customer should then make contact with you.

THREE FINDINGS ABOUT MAILSHOTS

1. It becomes more and more difficult to get the required attention. Even response rates of 1–2% are comparatively good.
2. A mailshot without a follow-up telephone call makes little sense.
3. From 1. and 2. it follows that you should go to a lot of effort and use all your creative powers when creating and organizing a mailshot. It is better not to do a mailshot than to do a bad one!

DESIGN OF THE MAILSHOT

Have you heard of **AIDA?** This is what your mailshot should trigger in the customer:

A Attention
I Interest
D Desire
A Action

Attention

The first objective of a mailshot is that it should not be thrown away! This is the hardest part in the composition of a mailshot. Concentrate all your creativity on this. Here are some ideas:

- *Exciting title*. Create a vision in the mind of the reader. You could introduce a product in the form of a headline such as 'Hot Winter 2003', or you could announce an energy-saving week with a 'Squirrel Campaign'.
- *Elegance*. The design will shape the reader's first impression. Take time to arrange your text and any pictures so that they are pleasing to the eye. (See Figure 11.6.)
- *Picture*. If your product is visually interesting, use a good picture to catch the reader's eye and to help them remember it.
- *Gimmick – something playful*. An unusual method of folding, punched envelopes, a gift, a folded paper sundial – these all increase the chance that the letter will not be immediately thrown away; however, the cost also increases. Product and gimmick must always be balanced. The content of your message must stand up to the expectations raised by the gimmick.

Interest

This means:

- understanding
- recognizing the benefits.

Put yourself into the shoes of your target group. Which benefits are they interested in? How can you put this across so that it is easily understood? Brevity is the soul of wit.

Figure 11.6.
Typical eye progression when reading a text. In general it is true that: we look in the same way that we read – from left to right; central elements are perceived with particular intensity; pictures are registered before text. Therefore clarifying text should come after the picture or to the right of it; otherwise the reading process stalls

A mailshot should be no more than one page. And it is not just the complete text that benefits from being brief – keep sentences and words concise and powerful. The optimum amount of text for someone to view is 12 syllables. Text that is important for the readers' understanding of your message should not be any longer.

Desire

In order for recognized benefits to be translated into desire, the customer must believe you. The less pressure you put on the reader the better your chance. You should therefore be restrained in your design. In a time when everything flashes and glitters, and mega and giga bargains are to be had, a more solid, self-aware modesty goes down very well.

Action

Your reader should now do something. Make this as easy as possible for him or her, for example by:

- *Tempo.* Have even shorter sentences at the end than at the beginning.
- *Concrete appeal – what should be done now.* 'Reply to this e-mail'; 'Register by 3 July'.
- *Testimonials.* Let satisfied customers say good things about your product. In this way third parties confirm your statements, which lowers the resistance threshold.
- *Gift.* If the cost is reasonable you could offer a gift: 'Wide-awake people who respond before 10 August will receive a solar alarm clock from us.' An early-booker discount is also a gift.
- *Preprinted reply.* A fax/e-mail/web form is standard these days. Just fill in the sender's details. It is often sufficient just to send back your mailshot. You will know from whom it comes by the personalized address.

CHECKLIST

If you think your draft mailshot is good, give it to someone who is not involved and ask him or her:

- Does the design appeal to you?
- Is the subject of the mailshot clear within five seconds?
- Have I formulated it clearly and positively?
- Does it have the desired effect on you?
- Is the message credible?
- How would you react to it?

Organization of the mailshot

Your well-formulated and well-designed mailshot will be put to best use through exceptional organization. Here are some tips:

- Who will phone to follow up the mailshot and when? You should give the recipient from one week to 10 days.
- How do you ensure that each customer has to deal with only one employee?
- How is customer interest logged?
- What happens if they are interested? The customer should get a reply from you within two days.
- Would you be able to deal with the orders if interest is very high? You may decide to send off the mailshot in stages.

MARKETING TIP

Use a current event for your mailshot that will have some personal meaning for the recipient. This enables you to build a bridge and create attention. Events can be anything from the weather to new laws, for example energy-saving regulations or a building restoration programme.

Brochures, sales documents

You need printed information for marketing. As the basis for this we recommend a leaflet that gives information about your company – a flyer. This should be professionally designed and printed. It is like a particularly attractive business card; it is a memory aid that you can give, for example, to interested parties on an exhibition stand.

In each case it is necessary to decide how much information is required (see Figure 11.7). You don't need an expensive, four-colour brochure for every purpose. What is important is that you have current information to hand for the most frequently asked questions. This can be information that you have put together in house, for example reference systems with a photo. A uniform appearance is worthwhile for those who require more information.

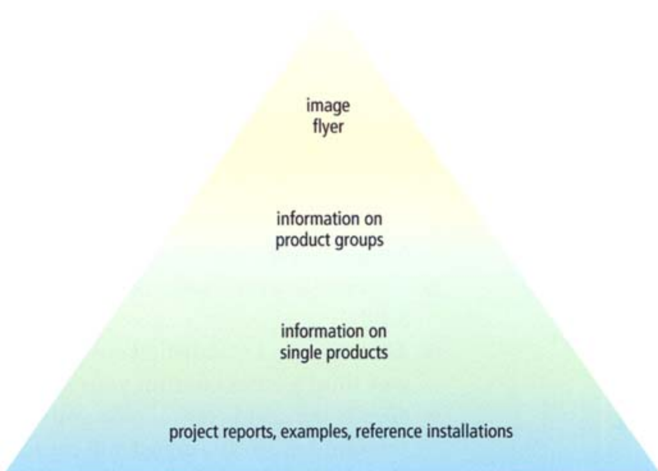


Figure 11.7. The publication pyramid. The further down the pyramid you go, the more simply the information can be configured

11.2.3.2 EVENTS

Events have a particular attraction. You make contact with lots of people over a short period of time. Preparation for and execution of an event is a motivating experience for the whole company. In addition, you may be able to get free coverage in the local press. However, events also take a great deal of preparation and require intensive personnel involvement. During an exhibition it is often only possible to continue with normal business in a limited way. In addition to the costs therefore, you may also have a lower revenue.

Some ideas for events:

- participation in exhibitions and trade fairs
- in-house exhibitions, open days
- participation in local campaigns or events
- product presentations, for example in a hotel
- customer seminars
- presentations.

Events are a tremendous opportunity to obtain addresses of interested parties. Don't take all your informational material with you – instead, offer to send information to anyone interested and in this way you will build up contact addresses. You will also prevent your expensive brochures from becoming yet more waste paper at exhibitions.

MARKETING TIP

Try thinking indirectly: for example, invite a local school class to a solar morning. You will not only enjoy passing on information, but will also gain 20–30 assistant sales staff – no one influences adults as well as children influence their parents!

11.2.3.3 PUBLIC MEDIA

If you want to reach a lot of people you have to use public media. Some examples are:

- the Internet
- press
- cinema
- radio
- television.

Today the Internet is more or less taken for granted. A complete section is devoted to it in this chapter (section 11.2.3.4).

With the press there are many options:

- advertisements
- inserts
- press information
- editorial coverage (a journalist writes about a subject that you have proposed).

Even smaller companies can make good use of the press, at least in the local area. Editors are always interested in new things: if you have installed a solar system on an eye-catching house or if a school class has created and installed a system with your help, then call the local press.

Sometimes a good picture is also sufficient to give you coverage: for example a mobile crane with a large system on its hook, or a system that is particularly architecturally attractive. Ask the journalists what interests them. Give them background information that is of general interest to them. Keep PR and advertising well apart. If you want pure advertising then go straight to the advertising department.

11.2.3.4 THE HOMEPAGE FOR SMALL BUSINESSES*

As a contact and presentation medium the Internet has great significance for marketing. Virtually all large and many small companies have an on-line presence. The following sections show why this is a worthwhile venture, and how resources can be optimally used to set up the Internet presence.

THE AIM OF A COMPANY WEBSITE

According to a corny joke on the Internet, company websites are created either for the boss, the designer or the customers. The aim of a commercial website must always be to gain customers and strengthen customer relationships. Internet sites that are created for pure vanity are therefore not a subject of this contribution. The practical use of a company website is to increase sales, either because the Internet site leads to and accompanies company development, or because it acts directly as a platform for the sale of goods. In the solar area the latter goal is still not easily realized and therefore requires special efforts, which we shall discuss at the end of this section.

CONTENTS OF A SMALL COMPANY WEBSITE

Websites should be of practical use to the customer. Content should be determined by the three W's rule: Who? What? Where? The following questions have to be answered:

- Who is being presented on the website?

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*Author: Dr. Eduard Heindl, Heindl Internet AG, eduard@heindl.de

- What can I obtain from this company?
- Where do I find the company in the real world?

To enable the customer to easily relate to the Internet site, the complete company name and logo, and the location at which the company operates must be on every page. A search engine will not normally recognise the geographical location in which the company running the website is located. However, customers will be interested in finding a company in a particular area.

Detailed information about the company and the products should be presented on separate pages. A fundamental rule applies to the presentation of information, independently of the respective products; these pages may well be somewhat more extensive than the homepage as the visitor expects precise information on the Internet.

Text should be made more appealing by use of meaningful pictures and graphics. The interested visitor also expects to be able to print out these pages, so they should be configured in such a way that no important information is lost when they are printed.

Company sites should include an accurate description of how to reach the company. This should include a description of the route in text form, and also a map. It must always be easy to print this page.

CONTACT BY E-MAIL AND SPECIAL FORMS

The Internet is the only advertising medium that permits direct contact without a change of media – an opportunity not to be neglected. A contact form must therefore be included on every website, which the customer can easily fill in and then transmit directly to the company by e-mail.

Some simple rules apply to the design of a form. The user should have to fill in as few fields as possible, normally it is sufficient to just have the name and e-mail address or telephone number. It is also sensible to include a free text field, so that the customer can also place a special enquiry. A 'call-back' field is a nice gesture, and tells potential customers that you are prepared to cover the telephone costs. What is essential for the effectiveness of on-line forms is that enquiries are processed quickly. It is worth doing this as the user already has a real interest in the company's services. Users generally expect a reaction on the same day or at the latest on the next working day. To succeed in this the company must clearly establish who reads and who responds to e-mails. Arrangements to cover holidays are essential, as a reply after several weeks is useless. As an alternative, the e-mail address of the company should also be published so that a customer can email the company. This also means that the customer can send photos, for example, at the same time

Figure 11.8.
The homepage should look inviting and immediately impart the most important information
Source: www.absak.com

MEASURING SUCCESS

Another special aspect of the Internet is the possibility of determining the number of visitors to the website at little expense. Almost all providers offer a web statistics function for this purpose. The important characteristic variables here are the number of pages called up and the number of visitors. Other variables, such as hits and data transfer, are meaningful to computer professionals but are normally otherwise of little interest. A good website should have at least one visitor per day, otherwise the cost of appearing on the web is not justifiable.

The success of a website, however, is measured not only by the number of visitors, but also by the number of enquiries and finally the increase in sales. This variable is very difficult to establish, as an on-line sale rarely takes place; however, the purchasing support often takes place via the Internet.

A simple calculation should make this clear. For an economically justifiable website the extra revenue should be greater than the cost of setting up and running the site. The costs of an Internet website are made up as follows:

$$C = S + L \times O$$

where C is the cost of the website over the amortization period, S is the set-up cost (one-off), O is the operating costs per annum, and L is the length of time on the Internet until the next major revision (amortization period).

The Internet can lead to new customers, who bring additional net revenue and possibly additional profit:

$$P = L \times A \times T \times M$$

where P is the additional profit, A is the additional customers per annum gained via the Internet, T is the average turnover per new customer per year, and M is the profit margin.

For example, the following values could apply to a larger business:

New customers, $A = 5$

Average turnover, T = €5000/\$5000/£3500 per annum per new customer

Profit margin, $M = 10\%$

Cost of setting up Internet site, S = €2500/\$2500/£1750

Operating costs per annum, O = €800/\$800/£560

Amortization period, L = 3 years

In euros:

$$C = S + L \times O = €2500 + 3\text{a} \times €800/\text{a} = €4900$$

$$P = L \times A \times T \times M = 3\text{a} \times 5 \times €5000/\text{a} \times 0.1 = €7500$$

In US dollars:

$$C = S + L \times O = \$2500 + 3\text{a} \times \$800/\text{a} = \$4900$$

$$P = L \times A \times T \times M = 3\text{a} \times 5 \times \$5000/\text{a} \times 0.1 = \$7500$$

In pounds sterling:

$$C = S + L \times O = £1750 + 3\text{a} \times £560/\text{a} = £3430$$

$$P = L \times A \times T \times M = 3\text{a} \times 5 \times £3500/\text{a} \times 0.1 = £5250$$

The additional profit is given by

$$P - C = €2600/\$2600/£1820$$

This means that an Internet appearance that costs about €2500/\$2500/£1750 with annual running costs of about €800/\$800/£560 is worthwhile in this case, as over three years it generates additional profit of €2600/\$2600/£1820.

COST OF IMPLEMENTATION

The costs of an Internet website are made up of four cost factors:

- web design
- web server
- web directory
- Internet access.

Certain key values should therefore be used for the calculation, which naturally depend significantly on the individual wishes.

The web design should always be done by a professional agency, otherwise it cannot be guaranteed that operation of the pages will be technically trouble-free. A professional company can also advise on legal issues concerning the information displayed. Pages that do not function are effectively anti-advertising! A well-designed site with 10 pages and a contact form will cost in the order of €2500/$2500/£1750 (depending on country and level of sophistication).

The web server is not set up in the company but at a provider. A simple site does not require a high-performance server, and thus the costs are around €300/$300/£210 per annum. A website must also be promoted within the Internet: the best way is to enter it in websites with specific themes and high visitor numbers. The Internet agency must also ensure that the site is easily found by search engines. Another €500/$500/£350 must be allowed for this each year. Your own Internet access, necessary in order to be able to answer e-mails, does not have to be calculated separately, as it will be mostly used for other purposes, and the cost is negligible in comparison to other items.

SERVICING COST

Those who take Internet marketing seriously and wish to gain more than a handful of new customers each year must also service their Internet site. Servicing mainly consists of updating the contents without visual changes.

Updating means 'moderate but regular changes'. It cannot be said often enough that it is only continuous servicing of the content that leads to noticeable advertising success. No customer expects daily news from a workshop, and certainly not 'current' offers for Christmas or Easter. In most cases three to four hours per month are sufficient to add information such as completed projects to the reference list, to announce appointments, and to delete old information. This work can be done with inexpensive editing systems, which permit web pages to be changed without knowledge of HTML and without endangering the layout.

ACTIVE ADVERTISING ON THE INTERNET

Advertising on the Internet differs from classical print media because the potential customer first has to be made aware of your homepage. There are several ways of doing this, the best of which is offered by the Internet itself and which is described here.

Search engines

Anyone who has used the Internet to solve a problem goes first to a search engine such as Google and enters a keyword or keywords. Out of the first 10 results a suitable site is visited, and if the site is good this can already be the start of a business relationship. It is therefore very important that your company appears high up the list. Internet sites should be optimized for search engines. For this to be successful the businessman must know by which search words he wishes to be found. There should also always be a regional reference, in which the place name appears on the Internet site. The site should then be submitted once to the search engines; repeated submission is unnecessary.

Portals

In the traditional media market, specialist magazines provide a service by attracting and retaining a target public. On the Internet this is done by subject-orientated portals. These have very high visitor numbers, which an individual company could rarely reach. It therefore makes sense for a company to draw attention to their own homepage within a portal. This can be done by placing an entry in a classified directory or by means of banner advertising and links.

Classified directory

There are now a huge number of classified directories ('yellow pages') on the Internet (Google found 114,000), but only very few in which it is worthwhile being entered. A good reference number demonstrating the significance of a classified directory is the number of visitors to the directory per annum.

Banner advertising

The most established form of advertising on the Internet is banner advertising. With banners it is possible to attract the attention of a wide public to a company and to entice new visitors to your own website. A banner is a small picture integrated into another website (see Figure 11.9). This picture is linked to your own site by a hyperlink. The visual configuration of the banner should be restricted to what is most essential. A 468 × 60 pixel area offers little space for text. For a banner to work it is therefore sensible to commission an agency for the graphical work. Banner advertising has the greatest effect when the target public is searching for related products and services. Therefore solar companies should place their banner on websites to do with building, heating, solar energy and environment, as potential customers can be gained there.

The price for banner advertising is usually calculated according to the number of hits and the banner size. According to the situation, between €10 and €50 ($10–50, £7–35) is charged per 1000 PV (page views).

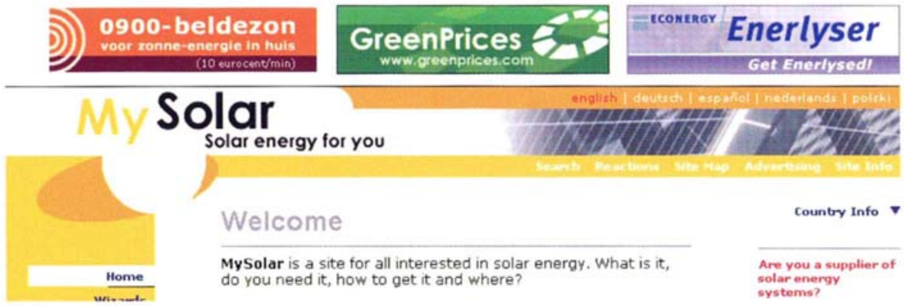

Figure 11.9.
Banner advertising should be placed where the potential customer surfs.
Source: www.mysolar.com

Links

A website should always be well linked within the Internet. Apart from the options of the classified directory and banner advertising already described, you should try to be mentioned on suppliers' pages with a link. Satisfied customers may also be prepared to have a link from their homepage to yours. In return, you should also be ready to include a link back from your own pages to the respective company.

DIRECT SALES THROUGH THE INTERNET

The Internet is not just a large shop window; it is also developing more and more into a marketplace. However, changes in purchasing behaviour are much slower than the acceptance of the new medium. The opportunities that are now on offer will be introduced here.

Suitable products

Not all products are equally suitable for selling over the Internet. On the one hand the product must be in a price class that represents a justifiable risk in dispatch and payment. On the other hand the product should be capable of being used without further support from the vendor. This is not the case for solar thermal and photovoltaic systems today; however, many other products in the photovoltaic area are well suited to the mail order business. In a sales analysis by Solarserverstores (www.solarserver.org) an optimum price of about €100/$100/£70 was established. Items that sell particularly well on the Internet are charging units and solar lamps, as well as solar-operated household articles and solar watches.

Next Page

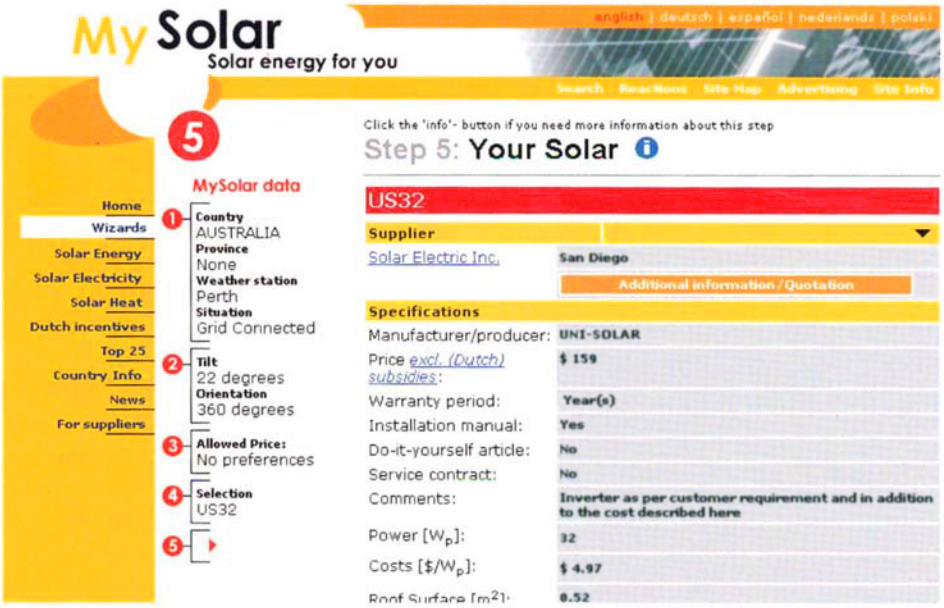

Figure 11.10.
Direct sales on the Internet can be completed with shop systems. The product prices must be accurately calculated.
Source: www.mysolar.com

Technical costs

An on-line shop requires very high investment, both for the software and the product entries as well as for the day-to-day operation. Today standardized program packages, the installation and operation of which require considerable experience, usually serve as shop software. This software must run on a powerful and very reliable computer, otherwise a high number of hits may cause delays or frequent server failures. It is therefore recommended that an experienced service provider, who can demonstrate comparable projects as reference, should carry out the implementation. The cost for technology and software in the first three years is at least €10,000/ $10,000/£7,000. On top of this there is a cost of about €50/$50/£35 for each product entered in the catalogue.

11.2.3.5 CUSTOMER RELATIONSHIPS

So far we have only discussed the winning of new customers. But what do you do with the customers that you have already gained? For most companies a large treasure chest remains buried in this area. It is seven times easier to reactivate an old customer than to gain a new one. Therefore customer focus as a theme is not only more enjoyable but is also the more successful approach.

Consistent customer focus in all customer relationships (Figure 11.11) is a culture in which the management must set an example and which they must also implement in all areas of the company. The installer should know exactly what was promised to the customer when the contract was awarded. Apart from neat craftsmanship he must also feel that he is responsible for cleanliness when working in the customer's house. He should also be aware how to professionally handle a special wish or a complaint by the customer. Some can do this naturally, but as a rule training is required.

MARKETING TIPS

- Carry out a mailshot campaign to your customers. Use a questionnaire to find out customer satisfaction and offer a small gift for returning it.
- Variant: Ask for details of acquaintances who may be interested in solar systems and offer a gift for every address.
- Alternative: Send a questionnaire with the invoice, which can be returned anonymously.

Satisfied customers help you to sell. Ask whether they would be willing to give a reference. If they agree, show your appreciation. The opportunity to ask existing customers about their experiences is worth much more to a potential customer than anything you can promise. The offer alone strengthens credibility. At the same time you are displaying customer care: the existing customer feels honoured and will probably also enjoy passing on his or her knowledge.

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For further information

ISES, the International Solar Energy Society, has a large on-line library of documents called WIRE available on http://wire.ises.org.

More information is given on different countries in Section 4.5.

Appendix A: Glossary

absorber The part of the solar collector that absorbs the incoming solar radiation, converts it to thermal energy, and feeds it into the heat transfer fluid. For an optimal conversion process at higher temperatures, the absorber is selectively coated (high absorption, low emission) and provided with a pipework system (heat transportation) through which the fluid flows (normally water or a water/antifreeze mix).

absorption coefficient, α The ratio of radiation absorbed by a surface to that of the incident radiation.

albedo (or *reflectance*) The ratio of solar radiation reflected by a surface to that incident on it. Examples: snow 0.8–0.9; woods 0.05–0.18.

annuity Describes the annual cost in terms of interest and repayments, starting with investment costs, the total period of repayments and an effective interest rate so that at the end of the period the debt has been repaid.

aperture area For flat collectors, the surface area of the collector opening through which unconcentrated solar radiation can enter the inside of the collector housing. For tube collectors the aperture surface of the product is calculated from the length and width of the absorber strips and the number of strips. If the gaps between the absorbers are closed with a reflector, the aperture surface increases correspondingly.

aquifer storage An underground, natural storage system, which serves as a seasonal store and utilizes the water-filled, porous earth layers: that is, the groundwater. Apart from water, rocks or boulders can also serve as a storage medium. Thus gravel–water storage systems are also described as aquifers.

azimuth The angular deviation of the collector surface with respect to the direction due south. In solar technology the azimuth angle is defined for south as $\alpha = 0°$: deviation to the west is positive, to the east it is negative.

back-up energy The energy that the consumer uses to supplement solar energy. Examples: oil, gas or electricity.

bleeders (air vents) In solar loops, air gathers in the highest positions and can interrupt the circulation of the fluid. To remove this air, bleeder valves (air vents) are installed at the critical points (highest points) of the solar loop. There are manual and automatic bleeders. The bleeders must be suitable for the transfer fluid type and the maximum temperature in the solar loop.

bypass If the solar loop consists of long pipe runs, the installation of a short-circuit to initially circumvent the heat exchanger is recommended. During short-circuit operation the medium is heated first in the collector circuit. The pipe to the heat exchanger is only opened via a pump or motor-operated valve if the fluid has a higher temperature than the store.

check valve Prevents undesirable fluid movement. Check valves are installed in pipeline systems if an unwanted reversal in the normal fluid direction can take place under certain operating conditions. There are non-return flaps or valves and gravity brakes. In solar systems this type of device is used to prevent the store heat from thermosyphoning up to the collectors if the circulating pump is switched off. In the cold water feed pipe, a check valve is installed so that heated water cannot be forced out of the store back into the rising main as a result of thermal expansion.

collector For domestic water heating, absorbers are housed in a box or an evacuated glass tube and then covered with a highly transparent cover with thermal insulation behind. This is in order to keep the heat losses as low as possible at the higher operating temperatures. The collector is then the absorber plus these other items. If a collector is only an absorber, it may only be suitable for low-temperature applications such as swimming pools. In the case of a glazed collector a differentiation is made between the absorber surface, the aperture surface and the gross surface. The *absorber surface* is the surface area of the absorber on which radiation is converted to heat and from which the heat is taken. The *aperture surface* is the collector opening for the solar radiation, which can then reach inside the collector housing. The *gross surface* is the total surface area of the collector (important for installation).

collector efficiency, η Gives the proportion of radiation striking the absorber surface that is converted to useful heat. It is dependent on the temperature difference between the absorber and the surroundings, and on the global solar irradiance. If the collector efficiency is represented on a diagram by means of the temperature difference between absorber and surroundings, the collector characteristic curves for a specific collector are obtained in terms of the irradiance.

convection Warm liquids or gases are lighter than cold ones and ascend. They thus carry the heat upwards. Examples: convection flows in the store (heated storage water moves upwards and cold water descends); convection losses in the collector (cooler air draws out the absorber heat and climbs upwards).

corrosion The decomposition of metallic materials. Corrosion is caused mainly by the different electrochemical potentials of two metals that are connected together so that they are electrically conducting and are wetted by an electrically conductive liquid. If corrosion is expected, suitable measures, such as the addition of inhibitors to the solar fluid or coating of system parts that are subject to weathering, should be taken to protect them from corrosion damage. In enamelled containers (solar stores) sacrificial or auxiliary current anodes are used to protect against corrosion at potential weak points. This generates a protective current in the store by means of a 'potentiostat', which prevents the precipitation of copper ions on the container wall.

CPC Compound parabolic concentrator; used in evacuated tube collectors to increase the aperture surface area by means of mirror reflectors in a geometrically optimized form as parabolic channels.

degree of efficiency, η Whenever energy is converted (such as when converting solar radiation into heat in the collector), losses occur (for example heat radiation). The degree of efficiency describes the ratio of useful energy (heat) to the energy used (solar radiation). The lower the degree of efficiency, the higher the losses. If a collector has a degree of efficiency of $\eta = 0.6$ it means that, of the radiation received, 60% is converted into useful heat, and 40% is lost in the form of optical and thermal losses.

degree of transmission, τ Part of the incoming radiation does not reach the absorber owing to reflection from the glass cover and absorption as it passes through the glass material. The degree of transmission describes the transparency of the glass pane.

degree of utilization Relates to a specific period of time – normally a year – and refers to the ratio of benefit (for example useful generated heat energy) to expenditure (energy used in the form of unburnt fuel, electrical energy or solar energy). The degree of utilization is normally lower than the degree of efficiency at the normal design point (nominal load) – that is, the utilization of a boiler, where the periods in which the boiler operates under partial load or start-up are also taken into account.

drainback system In these systems the heat transfer medium (water) is only in the collector during the pump running time, as it self-drains after the pump is switched off. On the one hand this prevents evaporation; on the other hand it means that frost protection agents are not required. Advantage: in comparison with a water/antifreeze mixture, water possesses a higher heat capacity and, as a result of its lower viscosity, causes lower pressure losses.

emission coefficient, ϵ Gives the amount of irradiated solar energy incident on the absorber (wavelengths 0.3–3.0 μm) that is radiated back again as infrared radiation (wavelengths 3.0–30 μm). An emission coefficient of 0.12 indicates that 12% of the solar energy converted to heat is radiated back.

energy Arises in different forms: thermal energy (heat), mechanical energy or electromagnetic energy (radiation). Energy is given in different units, for example as watt-hours (Wh), kilowatt-hours (kWh) or joules (J). One joule is one watt-second (Ws). 1 kWh = 1000 Wh = 3,600,000 J (= 3.6 MJ).

expansion bellows An intermediate piece made of corrugated copper tube. The expansion bellows compensate for temperature-related length changes to avoid cracks and leaks in the solar loop.

expansion vessel Part of the safety equipment for some solar hot water systems. It is a closed container with a nitrogen cushion separated by a membrane. In the event of expansion of the volume of the heat transfer liquid (water or water/antifreeze mix) caused by heating, it takes up this expansion. For a stagnation situation it also takes up the liquid content of the collector field.

getter To maintain a vacuum, various manufacturers integrate so-called 'getters' into the vacuum tubes. These can have either a barium sulphite coating that is vapour-deposited on the glass (that is, 'Thermomax') or copper cushions that are filled with a special granulate and fixed onto the absorber. In both cases the gas molecules are absorbed and the vacuum therefore remains stable over a long period. In the case of barium sulphite getters this process is visible by a colour change in the coating (the mirror surface becomes powdery white).

global solar radiation The atmosphere of the earth reduces the radiated power of the sun through absorption and scattering (= loss) by molecules, dust and clouds. The energy therefore changes direction and reaches the earth's surface partly as diffuse radiation. Without clouds, the solar energy can reach the surface directly. The term *global solar radiation* can be described as the full radiation impacting on a horizontal surface. It therefore consists of direct and diffuse radiation. With a clear sky, global solar irradiance consists only of direct radiation and with a cloudy sky only of diffuse radiation. As an annual average in northern Europe, diffuse radiation is between 50% and 60% of the global solar radiation. Diffuse radiation also heats up solar collectors.

gross heat yield, Q_{BWE} Corresponds to the heat discharge at the collector flow or at the inlet to the store. Measured in kWh/m^2. The pipe losses are included. The gross heat yields of different solar collectors can be compared only under the same temperature conditions (average absorber temperature and ambient temperature) and with the same irradiation conditions. It is also necessary to know whether it refers to the absorber, the aperture or gross surface area of the collector.

heat loss rate, kA The product of the heat loss coefficient, k, of the store and its surface area, A. Measured in W/K. If the kA value is multiplied by the temperature difference between the inside of the tank and its surroundings, the heat loss of the hot store is obtained. The kA value already includes the heat losses through heat leakage at the connections etc. Highly thermally insulated solar stores have kA values between 1.5 and 2 W/K, depending on size.

heat production costs Describes the economic viability of solar systems and gives the cost of a kilowatt-hour generated or saved with the help of the solar system. The investment and operating costs are taken into account, together with the energy savings.

heat pipe Vacuum tube of glass in which the absorber heat is extracted from within the glass via a closed pipe containing evaporative fluid and is then transferred to the main heat transfer fluid by means of a wet or dry manifold.

hysteresis The difference between the switch-on and switch-off temperatures of a relay; often found in a temperature difference controller.

inhibitor If different metallic materials are used in the solar loop, there is a risk of electrochemical corrosion. This can be eliminated by the addition of a suitable corrosion protection agent (inhibitor) to the heat transfer fluid. In closed systems, where the fluid contains an inhibitor, all the permitted metallic materials can be used in any combination. The inhibitor should have a certificate, which has to include details of the effective life.

intrinsic safety According to the Pressure Equipment Directive solar systems must be designed to be 'intrinsically safe'. Continuous heat take-up without heat consumption must not lead to a severe fault. A severe fault exists, for example, if fluid is blown out of the safety valve or vent and the solar loop has to be refilled before it is started up again. Intrinsic safety can be achieved by suitable dimensioning of all the safety devices in the solar loop.

irradiance, G The area-related irradiated power density of the solar radiation; measured in W/m^2.

***k*-value** of the collector The heat loss factor, k (unit W/m^{2}K), gives the design-specific heat loss of a collector. It describes, among other things, the insulating status of the collector. The smaller the k-value, the smaller the heat loss.

Legionella The rod-shaped bacteria that lead to Legionnaire's disease. Legionella cause two different diseases: the potentially fatal type of pneumonia, and a feverish, influenza-like illness that is not fatal. Legionella can be found in all waters except sea water. For multiplication they require, among other things, water temperatures between 30°C and 45°C, a pH value of 6–9, and iron in dissolved or undissolved form. At temperatures above 50°C they are destroyed. Infection takes place exclusively by breathing-in finely distributed water drops (aerosol): that is, under the shower or in 'spa baths'.

lightning protection If lightning protection is provided on the building then a solar system must also be integrated into the lightning protection system. In this case the collectors should be provided with lightning protection corresponding to the BS 6651 guidelines and installed by specialist personnel qualified for the purpose. Earth cables with a cross-section of at least 10 mm^2 and suitable tube clips are necessary.

low-flow operation Significantly reduced flow rate through a collector circuit with stronger heating of the heat transfer medium (water or antifreeze fluid) compared with normal flow (volumetric flow rate 10–15 l/m^{2}h). Advantages: higher collector flow temperature, and hence faster availability of hot water; smaller pipeline cross-sections; lower pump power.

optical degree of efficiency (also **conversion factor), η_0** The proportion of the radiation falling onto the collector that can be converted to heat in the absorber. It is the product of the degree of transmission of the transparent cover and the absorption coefficient of the absorber surface: $\eta_0 = \tau \times \alpha$. The optical degree of efficiency corresponds exactly with the collector degree of efficiency if the temperature of the absorber is equal to the temperature of the surrounding air and no thermal losses occur.

overheating protection If, during a long period of sunny weather, no energy is removed from the solar store, the temperature can climb to a maximum limit. In such a case the solar loop circulating pump must be switched off. As a result, the absorber temperature climbs to the stagnation temperature and part of the transfer fluid evaporates. To avoid this undesirable state as far as possible, it is recommended that an additional overheating protection device is used to ensure that the maximum temperature is not even reached in the solar storage tank under such conditions. For example, during critical operating phases excess energy can be fed via the auxiliary heating circuit. Glazed flat-plate collectors and vacuum tubes are designed to withstand the stagnation temperatures for a long time.

payback time The economical meaning is the amortization period of the solar system (capital repayment time). It also means the time after which the solar system has gained the exact amount of energy that was required for its production (ecological amortization time).

pellets Made from dry, unrefined scrap wood (sawdust and wood shavings). They ideally have a diameter of 6 mm and are 10–13 mm long. One kilogram of wooden pellets has a calorific value of about 5 kWh. They require only half the storage volume of bulk wood. Wooden pellet burners can be used as combination systems in connection with a solar thermal system for domestic water heating as well as for room heating support.

potential, electrochemical (electrochemical series of metals) The greater the electric potential of a metal, the more precious the metal. As the base metals are dissolved by the more precious metals, it is necessary to consider this electrochemical series when using different metals to avoid corrosion damage. In the flow direction the more base metals must follow the more precious metals.

Element	Lead	Tin	Copper	Zinc	Aluminium
Potential	0.13	0.14	0.34	0.76	1.66

power The energy consumed or provided over a given time. Its unit is the watt (W), kilowatt (kW), joule per second (J/s) or kilocalorie per hour (kcal/h). 1 kW = 1000 W = 1000 J/s = 860 kcal/h. Example of calculating power: if a boiler provides 1500 operating hours of heat in a year and thereby generates 30,000 kWh it has an average power of 20 kW.

primary energy The energy originally provided by nature in the form of crude oil, coal, natural gas or radiation from the sun. Primary energies are partly used directly by the end user. For the most part, however, primary energy is first converted to secondary energy and then to end energy.

priority switching Pump controllers for conventional heating systems are usually designed so that the connected domestic water heating is prioritised. If the hot water temperature in the standby store falls below a set value and the store-charging pump is switched on, the heating circuit is not supplied and rapid heating of the hot water can take place. Priority switching is also effective if a solar store is connected to the storage charging circuit of a boiler that can be conventionally charged as necessary.

secondary circulation system To increase convenience, especially in the case of long domestic water pipelines, a secondary circulation system is installed that leads domestic water by means of a circulation circuit pump past the taps to the store. In this way, hot water is directly available when necessary at the taps. The circulation system can cause considerable heat losses. The important things here are the running time of the circulating pump and the quality of the thermal insulation on the circulation lines. Pressure switches and pulse-controlled or timer-controlled pumps can be installed to reduce circulation losses.

secondary energy Arises by converting primary energy: for example, coal is processed into coke or briquettes, crude oil into petrol, diesel fuel or heating oil.

selective coating On the surface of every body the heat radiation increases significantly with increase in temperature. To reduce radiation losses due to emittance (= emission) of long-wave heat radiation, the absorbers can be coated selectively in a special process. In contrast to normal black paints, this has an alternative layer structure that optimizes the conversion from short-wave to long-wave heat radiation and keeps its radiation as low as possible.

solar degree of utilization The ratio of the solar radiation striking the collector over a given time period, which has been converted into useful heat.

system efficiency Describes the efficiency of the whole solar system (collectors, pipelines, heat exchanger and storage tank). It shows how much of the solar energy irradiated to the collector can be used as hot water. It is true that over-sized systems possess a high solar fraction but, because of the non-usable excess heat in summer, they have a low degree of system efficiency.

solar fraction Also called the solar coverage rate. Indicates the ratio of the energy used for domestic water heating that can be covered by the solar system as an annual average. It corresponds with the ratio of the solar energy yield to the total energy requirement for domestic water heating, for the coverage of the solar store losses and any other losses in the circulation system.

solar constant Gives the irradiance at the upper edge of the atmosphere. It is on average 1367 W/m^2 (variations are caused by variable distances between the earth and the sun and variations of the solar activity).

stagnation temperature If the solar loop does not transmit the energy from the collector during high radiation, the absorber heats up to very high temperatures. If then the heat losses to the surroundings are just as great as the solar gain, the absorber will reach its maximum temperature. The value of the stagnation temperature is strongly dependent on the type of collector.

stratification index Represents the retention of temperature layers of fluid during draw-off. High stratification indexes mean good retention of temperature layers. The influence of the stratification index on the solar fraction is low: an increase from 30 to 100 leads to an increase in the solar fraction of about 1%.

system performance figure The ratio between the useful solar energy gained and the non-useful, parasitic electrical energy consumption of the pump and the control system.

thermosyphon principle Because of the difference in densities between warmer and cooler water, the warm water becomes more buoyant and rises upwards. This effect is supported in good solar stores by means of internal fittings so that, even after short solar system operating time, sufficient domestic hot water is available at the top of the tank. In gravity systems this effect is used as the only means of operating the solar loop.

thermostatic mixing valve If there is a high maximum temperature of the store, a mixing valve is required to prevent scalding when a tap is turned on. This is installed between the cold water supply pipe and the hot water take-off pipe. By means of the thermostatically controlled mixing in of cold water the maximum temperature of the water at the tap can be controlled within adjustable limits.

Tichelmann principle A collector field (array) can operate at its maximum performance only if the heat transfer medium (water or antifreeze fluid) cools the whole absorber surface area uniformly. It is thus necessary to ensure that, when the collectors are connected together, no areas are created through which the heat transfer medium either does not flow or does not flow through sufficiently. This is achieved by ensuring that all flow paths through the collector field have the same flow resistance; in other words they have the same length and cross-section. If the collectors are arranged according to the Tichelmann principle these conditions are fulfilled.

thermal conductivity, λ Characteristic value for the quality of the thermal conductance in solid bodies. The unit is W/mK. Thermal insulation has λ values between 0.035 and 0.045 W/mK.

thermal conductivity, effective vertical, λer Gives information to show how a temperature stratification stage breaks down in a static storage tank. The effective vertical thermal conductivity should be as low as possible. Good stores without internal fittings (for example without an immersed heat exchanger) have values that are in the range of the thermal conductivity of the water itself (approximately 0.6 W/mK). For stores with internal heat exchangers, the effective vertical thermal conductivity is about 1–1.5 W/mK. Simulation calculations have shown that, by halving the effective vertical thermal conductivity from 2.2 to 1.1 W/mK, the annual solar fraction can be increased by 5%.

usable energy High-grade energy that, after conversion from low grade (that is, perhaps in a boiler), is then available in a more useful form of hot water under the shower or in the form of heat in the living areas.

viscosity The viscosity of fluids depends strongly on the temperature. The viscosity of the transfer fluid (water or antifreeze fluid) is also dependent on the concentration of any additives such as antifreeze.

INDEX

Index Terms **Links**

Page numbers in *italics* refer to figures and tables

A

Index Terms	Links						

Index Terms	Links						

R

Index Terms	**Links**						

Index Terms | Links