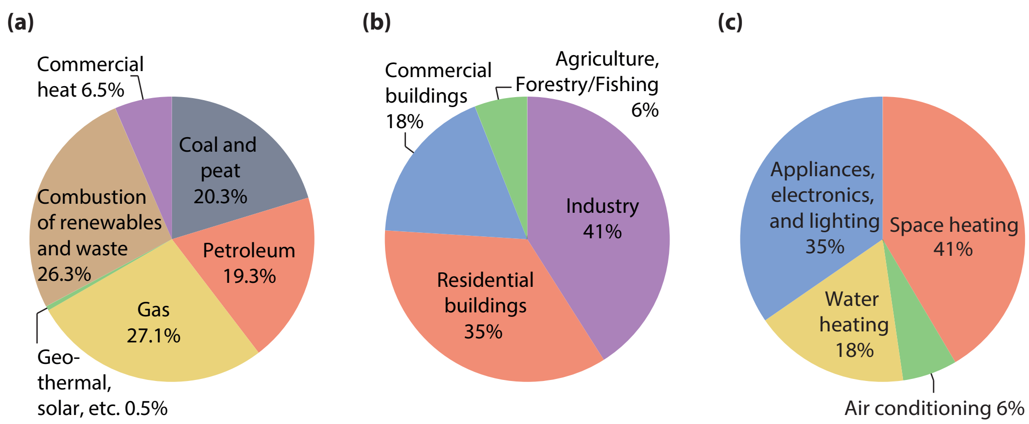

Figure 22.4: (a) The used primary energy suppliers for the generation of heat and (b) the demand of heat by sector [13]. (c) Energy consumption of U.S. homes [183]. All data is for 2009. Percentage of gas in (a) might be significantly higher nowadays due to the strong growth in shale gas usage (©OECD/IEA 2012, Insights Series 2012: Policies for renewable heat, IEA Publishing. Licence: www.iea.org/t&c/termsandconditions).

where M is given in $\mathrm{W/m^2}$ and $\sigma \approx 5.670 \cdot 10^{-8}\,\mathrm{W/(m^2K^4)}$ is the Stefan-Boltzmann constant. In nature, no black bodies exist. However we can describe them as so-called *grey bodies*. The energy emitted by a grey body still can be described by Plank's law [Eq. (5.18a)] when it is multiplied with a wavelength dependent emission coefficient $\epsilon(\lambda)$. For a blackbody we would have $\epsilon(\lambda) \equiv 1$.

22.2 Solar thermal heating

About half of the world's energy consumption is in the form of *heat*. About two thirds of the heat demand is covered by coal, oil, and natural gas, as we can see in Fig. 22.4 (a). As shown in Fig. 22.4 (b), heat is mainly used in the industrial sector for facilitating for example chemical processes and in the residential sector for heating and warm water supply.

Figure 22.4 (c) shows the total energy demand of a typical household in the United States. We see that space heating and water heating represent 59% of the total energy consumption. If also the demand for cooling is taken into account, about two third of the energy consumption are related to the use of heat.

The residential demand for heat can at least partially covered with a *solar water heater*, which is a combination of a solar collector array, an energy transfer system and a storage tank, as sketched in Fig. 22.5. The main part of a solar water heater is the *collector array*, which absorbs solar radiation and converts it into heat. This heat is absorbed by a heat transfer fluid that passes through the collector. The heat can be stored or used directly. The amount of the hot water produced by a solar water heater throughout a year depends on the type and size of the solar collector array, the size of the water storage, the amount of sunshine available at the site and the seasonal hot water demand pattern.

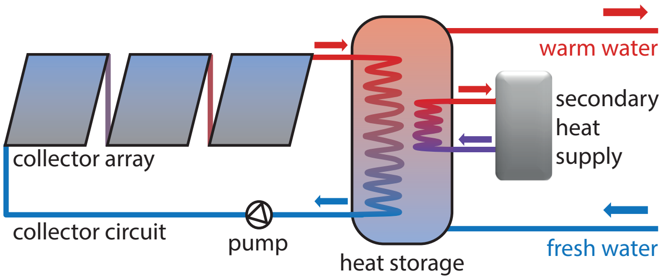

Figure 22.5: Illustrating the main components of a solar water heating system.

There are several ways to classify solar water heating systems. The first way is by the fluid heated in the collector. When the fluid used in the application is the same that is heated in the collector it is called a direct or open loop. In contrast, when the fluid heated in the collector goes to a heat exchanger to heat up the utility fluid, it is called an indirect or closed loop.

The second way to classify the systems is by the way the heat transfer fluid is transported. This can either be passive, where no pumps are required, or by forced circulation, using a pump. The passive solar water heating systems, uses natural convection to transport the fluid from the collector to the storage. This happens because the density of the fluid drops when the temperature increases, such that the fluid rises from the bottom to the top of the collector – this is the same as natural convection that we discussed in Section 22.1. The advantage of passive systems is that they do not require any pumps or controllers, which makes them very reliable and durable. However, depending on the quality of the used water, pipes can be clogged, which considerably reduced the flow rate.

On the other hand, active systems like the one sketched in Fig. 22.5 require pumps that force the fluid to circulate from the collector to the storage tank and the rest of the circuit. These systems usually are more expensive than passive systems. However, they have the advantage that the flow rates can be tuned more easily.

22.2.1 Solar Thermal Collectors

Now we will take a closer look at the solar collector, in which the working fluid is heated by the solar radiation. The collector determines how efficiently the incident light is used. It usually consists of a black surface, called the absorber, and a transparent cover. The absorber is able to absorb most of the incident energy from the sun, Q_{sun}, raising its temperature and transferring that heat to a working fluid. Hence, the absorber can be cooled and the heat can be transferred elsewhere.

Not all of Q_{sun} can be used, as there are some losses, as illustrated in Fig. 22.6. A part Q_{refl} is lost as reflection either in the encapsulation or in the absorber itself. Other losses are related to the heat exchanged with the surrounding air by the convection mechanism, Q_{conv} and radiation from the hot absorber, Q_{rad}. When we put all these energies in an energy balance, we find for the heat Q_{col} that can be collected by the collector

$$Q_{\text{col}} = Q_{\text{sun}} - Q_{\text{refl}} - Q_{\text{conv}} - Q_{\text{rad}}. \tag{22.6}$$

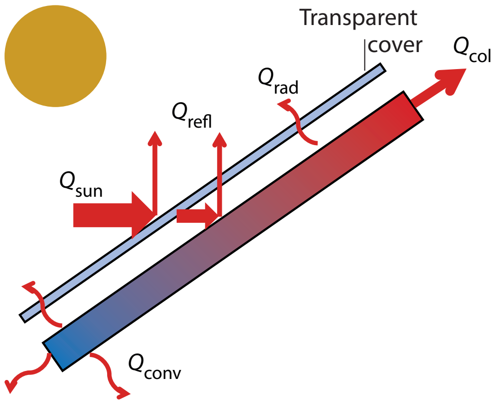

Figure 22.6: Illustrating the major energy fluxes in a covered solar collector.

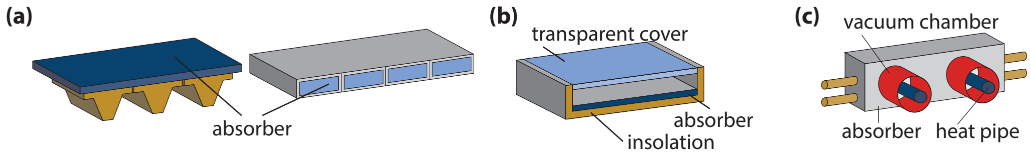

Figure 22.7: Illustrating (a) an uncovered, (b) a covered and (c) a vacuum collector.

The efficiency of the collector depends mainly on two factors: the extent to which the sunlight is converted into heat by the absorber and the heat losses to the surroundings. It will therefore depend on the weather conditions and the characteristics of the collector itself. To reduce losses, insulation from the surroundings is important, especially when the temperature difference between the absorber and the ambient is high.

Usually, collectors are classified in three categories: uncovered, covered and vacuum, as shown in Fig. 22.7. *Uncovered collectors* do not have a transparent cover, so the sun strikes directly the absorber surface, hence the reflection losses are minimised. This collector type only is used for applications where the temperature differences between the absorber and the surroundings are small, for example for swimming pools. *Covered collectors* are covered by a transparent material, providing extra insulation but also increasing the reflection losses. These collectors are used for absorber temperatures of up to 100°C. Finally, in *vacuum collectors* the absorber is confined in vacuum tubes. In that case, little heat is lost to the surroundings. The manufacturing process of these collectors in more complicated and expensive, but the collector can be used for high temperature applications since the convection losses to the surroundings are much lower than for the other types.

Modern solar collectors often use light management techniques just as solar cells. For example, transparent conducting oxide layers at the front window, that we discussed in Section 13.1, can be used. If they have the plasma frequency in the infrared, almost all the solar radiation can enter the window, but the long-wavelength infrared radiation originating from the hot parts in the collector cannot leave the collector as it is reflected back at the window.

Collectors also can be classified by their shape: we can distinguish between *flat-plate* collectors and *concentrating* collectors. *Flat-plate collectors* consist of flat absorbers that are oriented towards the sun. They can deliver moderate temperatures, up to around 100°C. They use both direct and diffuse solar radiation and no tracking systems are required. Their main applications are solar water heating, heating of building, air conditioning and industrial processes heat. In contrast, *concentrating collectors* are suited for systems that require a higher temperature than achievable with flat collectors. The performance of concentrating collectors can be optimised by decreasing the area of heat loss. This is done by placing an optical device in between the source of radiation and the energy absorbing surface. Because of this optical device the absorber will be smaller and hence will have a lower heat loss compared to a flat-plate collector at the same absorber temperature. One disadvantage of concentrator systems is that they require a tracking system to maximise the incident radiation at all times. This increases the cost and leads to additional maintenance requirements.

Just as for PV systems,[2] also for solar heat collector arrays it is important to decide whether the collectors should be connected in series or in parallel. Connecting collectors in parallel means that all collectors have the same input temperature, while for collectors connected in series the outlet temperature of one collector is the input temperature of the next collector. Most commercial and industrial systems require a large number of collectors to satisfy the heating demand. Therefore most of the time, a combination of collectors in series and in parallel is used. Parallel flow is used more frequently because it is inherently balanced and minimises the pressure drop. In the end, the choice of series or parallel arrangement will ultimately depend on the temperature required by the application the system.

22.2.2 Heat storage

Now we will discuss the heat storage, which is an extremely important component as it has an enormous influence on the overall system cost, performance and reliability. Its design affects the other basic elements such as the collector or the thermal distribution system. The task of the storage is twofold. First, it improves the utilisation of the collected solar energy. Secondly, it improves the system efficiency by preventing the fluid flowing through the collectors from quickly reaching high temperatures.

Several storage technologies are available; some of them can even be combined to cover daily and seasonal fluctuations. In general, heat can be stored in liquids, solids or phase-change materials, abbreviated as PCM. Water is the most frequently used storage medium for liquid systems, because it is inexpensive, non-toxic, and it has a high specific heat capacity. In addition, the energy can be transported by the storage water itself, without the need for additional heat exchangers.

The usable energy stored in a water tank can be calculated with

$$Q_{\text{stored}} = V\rho C_p \Delta T, \tag{22.7}$$

where V is the volume of the tank, ρ is the density of water, C_p is the specific heat capacity of water and ΔT is the temperature range of operation. The lower temperature limit is often

[2] See Chapter 15.

set by external boundaries, such as the temperature of the cold water, or by specific process requirements. The upper limit may be determined by the process, the vapour pressure of the liquid or the heat loss of the water storage. For example, for residential water heating systems the maximally allowed temperature is set to 80°C because at higher temperatures calcium carbonate will be released from the water, clogging the warm water tubes [184].

The heat loss of the tank, $\dot{Q}_{\text{loss}}$, can be determined with

$$\dot{Q}_{\text{loss}} = UA\Delta T, \tag{22.8}$$

where A is the area of the heat storage tank. U is the global heat exchange coefficient and is a measure for the quality of the insulation. Usually it varies between 2 and 10 W/K. Further, U is also a function of the different media between which the heat exchange takes place.

The same principles can be applied to small and big storage systems. Small water energy storage can cover daily fluctuations and is usually in the form of water tanks with volumes from several hundreds of litres up to several thousands of litres. Large storage systems can be used as a seasonal storage. Often they are realised as underground reservoirs.

Another type of energy storage are so-called *packed beds*, which are based on heat storage in solids. They use the heat capacity of a bed of loosely packed particulate material to store the heat. A fluid, usually air, is circulated through the bed to add or remove energy. A variety of solids can be used, rock being the most common. In operation, flow is maintained through the bed in one direction during addition of heat and in the opposite direction during removal. The bed is in general heated during the day with hot air from the collector. In the evening and during night energy is removed with air temperatures around 20°C flowing upward.

Another way to store heat in buildings is to use the solids of that the walls and roofs are built as a storage material. A case of particular interest is the *collector-storage wall*, which is arranged such that the solar radiation is transmitted through a glazing and absorbed in one side of the wall. As a result, the temperature of the wall increases and the energy can be transferred from the wall to the room by radiation and convection. Some of these walls are vented to transfer more energy to the room via forced convection.

The last method to store heat that we will discuss is to use phase change materials (PCM). While in all the storage methods discussed so far energy is stored as sensible heat, in PCM storage takes place as *latent heat*, which is used for a phase change, without any change in the material temperature. PCM used for energy storage must have a high specific latent heat L, such that a large amount of energy can be stored. In addition, the phase change must be reversible, and survive cycles without significant degradation. The stored amount of heat can be calculated with

$$Q_{\text{stored}} = m\left[C_s(T^* - T_1) + L + C_l(T_2 - T^*)\right], \tag{22.9}$$

where the different temperatures are also sketched in Fig. 22.1. We consider the specific heat capacity in the solid phase, C_s, to be constant from the initial temperature T_1 up to the phase change temperature T^*, the latent heat of the material L and the specific heat capacity in the liquid phase C_l from T^* up to the final temperature T_2. Materials that are commonly used s PCM are molten salts, such as sodium sulphate (Na_2SO_4), calcium chloride ($CaCl_2$) or magnesium chloride ($MgCl_2$). PCM storage in general is used for high temperature applications.

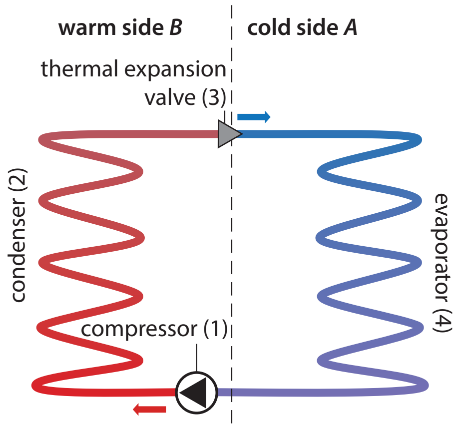

Figure 22.8: A compressor-driven cooling circuit.

22.2.3 System design

Often, at least at larger latitudes with large differences between summer and winter, solar thermal systems include a boiler as a backup. Its main function is to provide the necessary energy when the solar power is not sufficient. It is basically a normal heater that adds the remaining heat needed to achieve the desired temperature in the storage tank. As energy source, usually natural gas, oil, or biomass is used. Sometimes, the additional heat also is provided with electricity or a heat pump.

Up to now we discussed how to collect and store the energy, but we did not consider yet how to transport it from the collector to the storage system. The transport of heat is done with a *collector circuit*, which usually transports heat using either a liquid or gas. If a liquid is used, it is important that it neither should freeze nor boil, even at the most extreme operating conditions. Further, the medium should have a large specific heat capacity, a low viscosity, and it should be non-toxic, cheap and abundant. The most common fluids are water, oils or air.

As mentioned above, the flux can be caused either naturally by the temperature gradients, forced by a pump, or by a heat pipe, in which the fluid is allowed to boil and condense again. The optimal choice will depend on the specific system design. Further, heat losses in the collector circuit must be taken into account, especially when the pipes are very long. During the planning phase it therefore is important to minimise the circuit length.

In systems with a pump often a *controller* is present that regulates the fluxes of fluid through the collector, the storage and the boiler in order to assure the desired temperature of the. This can for example be done by calculating the optimal flux in dependence of the fluid temperature at the collectors and in the storage such that the heat transfer is maximised.

22.2.4 Solar cooling

Another interesting application is *solar cooling* (also called *solar air conditioning*), which seems a bit contradictory on first sight. Before we start with the actual discussion on solar air conditioning, we briefly recap the principle of a air conditioning system based on the *vapour-compression cycle*, which is sketched in Fig. 22.8. Similar to every *heat pump*, the task of this cycle is to transport heat from a cool reservoir B to a warmer reservoir A. Such a system has typically four components: a compressor, a condenser, a thermal expansion valve (throttle) and an evaporator.

In the compressor (1), vaporised coolant is compressed to a higher pressure. Under release of its latent heat to the surroundings, it is condensed to its liquid state in the condenser (2). Then the coolant passes a thermal expansion valve (3), such that its pressure on the other side of this valve is so low that it can evaporated again. For the evaporation, it must absorb latent heat from the cool reservoir A. Then, the coolant containing the latent heat from A is compressed again. We see that this cooling circuit utilises the latent heat stored and released during phase changes.

Naturally, heat only flows from warm to cold reservoirs. For reversing the heat flow, as it happens in a heat engine, additional energy must be added to the system. This happens in the compressor and traditionally is supplied as electric energy. Probably the simplest option to realise solar cooling is to generate this electricity by a conventional PV system or a solar thermal power system as discussed in Section 22.3. Further, it is also possible to drive the compressor with mechanic energy obtained from solar energy directly with a Rankine cycle, which is discussed in 22.3.

The choice of the *coolant* is based on the temperature regime in which the cooling system will operate. However, also their effect on the environment has to be taken into account. For example, *chlorofluorocarbons*, which were widely used as coolants, were heavily regulated in the 1980s because of their destructive effect on the ozone layer [185].

Another concept that that directly can be driven by solar heat is that of an *absorption cooling machine*. In difference to compressor-driven cooling, no mechanical energy is required for absorption cooling, but the cooling process is directly driven by heat that can be supplied by solar collectors. Instead of one coolant, here *two substances* are used: a *refrigerant* and an *solvent*. Often, ammonia (NH_3) is used as refrigerant, while water is used as solvent. Under atmospheric pressure, ammonia has a boiling point of -33°C. Further, it is very soluble in water, a property that is utilised in the cooling process.

Figure 22.9 sketches an absorption cooler. In the generator (1), a mixture of both substances is heated with an external heat supply (for example from a solar collector). Because of its low boiling point the refrigerant will leave the mixture in the gas phase. The solvent still present in this gas is separated and brought back into the boiler (not drawn). Then, the refrigerant is condensed in a condenser (2) and brought to a thermal expansion valve (3). Similar to the compressor circuit, latent heat is used to evaporate the expanded refrigerant (4), such that cooling takes place. Next, the refrigerant is absorbed by the solvent (5) and the refrigerant-rich solvent is pumped back into the generator using a solvent pump (6). The solvent circuit is closed with the solvent flowing from the generator (1) to the absorber (5). A heat exchanger (7) between the two branches of the solvent cycle prevents heat from flowing to the generator side, hence reducing the necessary heat supply.

Instead of using a throttle valve (3) to expand the refrigerant, it also can be mixed with a third gas, for example hydrogen (H_2), such that the partial pressure of the refrigerant

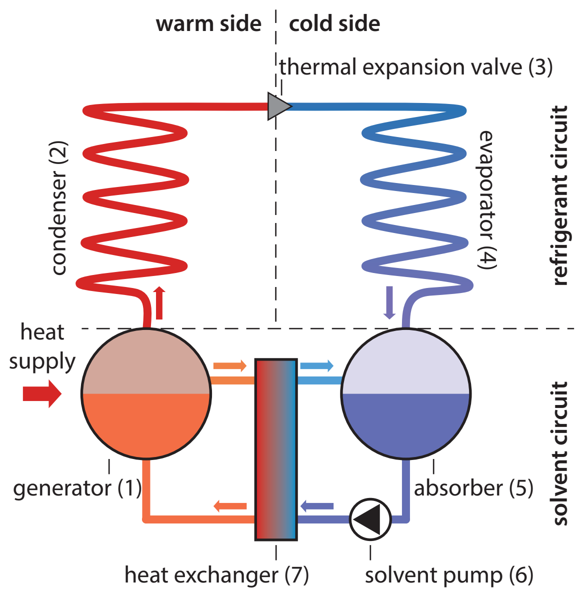

Figure 22.9: Illustrating an absorption cooling circuit. The numbers are explained in the text.

is reduced allowing it to evaporate. In that version, the whole system operates at one pressure.

The last option of cooling that we discuss is that of solar *desiccant cooling*, illustrated in Fig. 22.10. In such a system, air is dried when passing through a desiccant, like silica. Next, the air passes a heat exchanger where a large fraction of the heat is already taken out of the air stream and transported to the outgoing air stream. Then, water is sprayed into the air. As it evaporates, the air is cooled and humidified, such that it guarantees optimal interior conditions. Air that leaves the interior is first preheated passing the heat exchanger and then heated up further using a solar collector. The hot air streams through the desiccant. Hence, the desiccant is dried and can be reused for adsorbing humidity.

22.3 Concentrated solar power (CSP)

In this section we take a closer look at *concentrated solar power* (CSP), where high temperature fluids are used in steam turbines to produce electricity. Much of the early attention on CSP systems was on small-scale applications, mainly for water pumping. However, since about 1985 several large-scale power systems with a power output up to 80 MW have been built.

The CSP technology is especially interesting for desert regions, where almost all the solar radiation is incident as direct radiation. As illustrated in Fig. 22.11, these systems consist basically of a collector, where the solar energy is absorbed, a storage system, usually water or phase-change storage, a boiler that acts as a heat exchanger between the operational fluids of the collector and the heat engine, and the heat engine itself, which