EMS717U/EMS717P

Renewable Energy Sources

Solar Thermal Systems

Content

- **Solar thermal system:** Passive solar thermal space heating, solar thermal engines, solar hot water heating, solar chimney, solar assisted heat pump systems.
- **Solar hot water heating system:** configuration and components
- **Design of solar hot water heating system:** worked example

Solar thermal systems

Solar Thermal Energy Systems

Solar thermal energy systems involve capture of solar radiation as heat

Types of Solar thermal systems

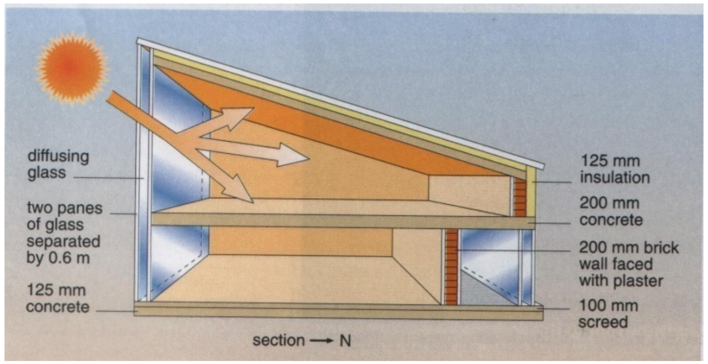
1) Passive solar thermal space heating

These involve the absorption of solar energy directly into buildings for space heating applications. These systems usually use circulated air to transfer collected energy without the use of pumps.

Typical systems raise outside air temperature by between 5 to 15 ºC to provide a portion of the space heating load – remainder supplied by conventional heating.

Most effective when integrated into new building as part of low energy building design.

Possible to reduce conventional space heating requirement of a building by between 20 – 50%.



Examples of solar thermal air heating

Solar Thermal Energy Systems

Types of Solar thermal systems

2) Solar thermal engines

An extension of active solar heating involving more complex solar collectors or concentrators that are capable of producing temperatures in excess of 100 ºC – high enough to produce steam to drive turbines for electricity generation

Example of a Solar thermal engine surrounded by a heliostat concentrator field

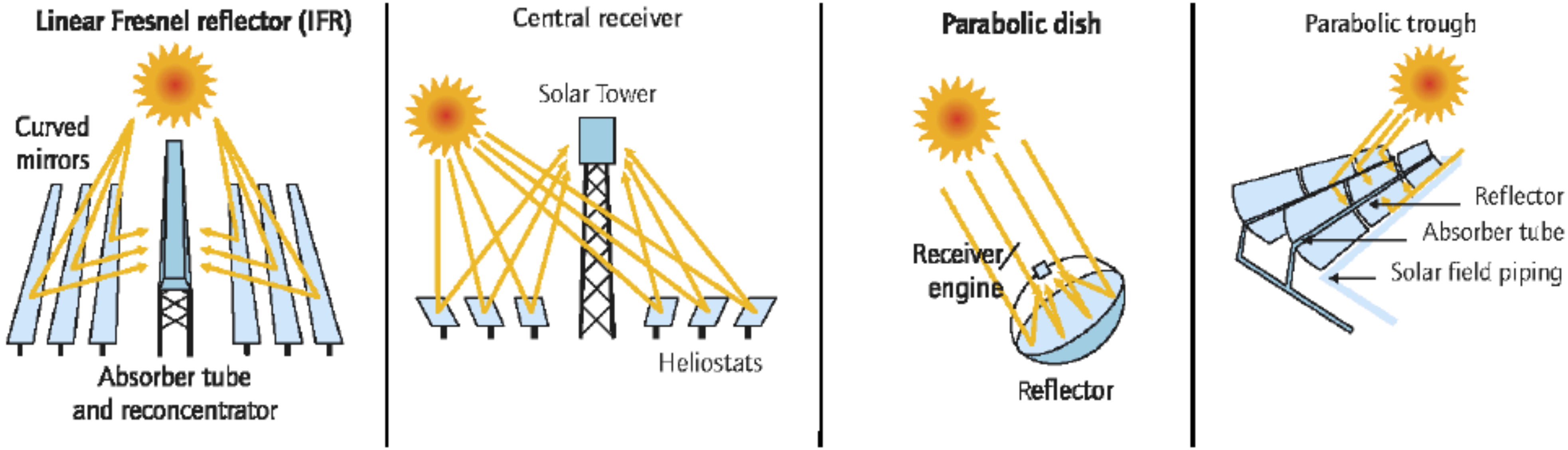
SEGS solar collector field at Kramer Junction, California (source: Boyle, G., *Renewable Energy* (2000))

Example of a 2-D parabolic trough concentrator in operation is that of the Solar Electricity Generating Systems (SEGS) at Kramer Junction, CA.

Power plant has a collector area of 464,000 m^2 capable of generating 80 MW of electricity by heating synthetic oil to 390 ºC which is then used to produce high temperature steam.

Efficiency of 20% possible which is competitive with commercially available photovoltaic systems

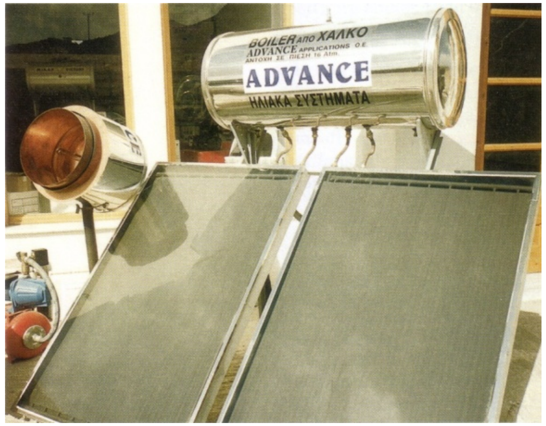
Figure 13. Main CSP technologies



Source: IEA (2010), *Technology Roadmap: Solar thermal electricity.*

Most existing CSP plants are based on trough technology, but the majority of projects under development now employ tower systems.

Solar thermal energy systems involve capture of solar radiation as heat



Solar thermal water heater
(Thermosyphon) unit

Types of Solar thermal systems

3) Solar water heating systems

These always involve a discrete solar collector device to gather the sun's radiation for use as heat.

Most collectors are simple systems and the generated heat will be below 100 ºC for use as domestic hot water or swimming pool heating

Most common application is for domestic hot water systems (DHWS) that are generally sold as 'off-the-shelf' ready made systems (Thermosyphon kits).

Other applications using custom designed systems include provision of process hot water for commercial and institutional uses such as, schools, hospitals, office buildings and large apartment buildings.

Solar Thermal Energy Systems

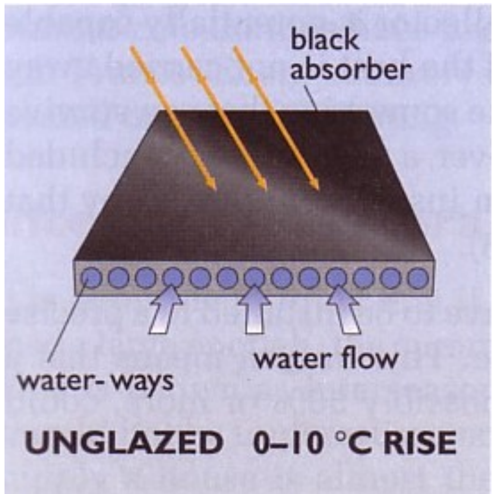
Solar Water Heating Applications

2) Swimming pool heating

Used to regulate the temperature in swimming pools, extending the swimming pool season and saving on conventional energy costs. Use same basic principle as service hot water systems but swimming pool itself is heat storage.

Captured large share of market as most cost effective system – reduced costs due to simplified collector system - no glazing due to lower temperature

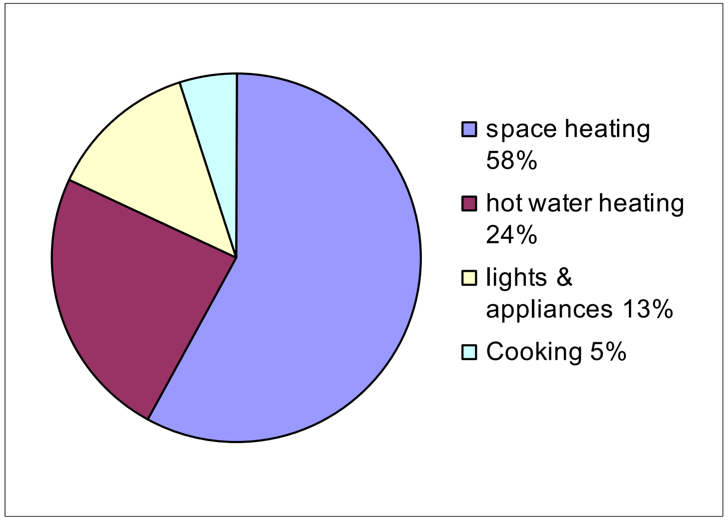
Require temperatures rise typically ~10 ºC



Unglazed flat-plate collector

Space and Water Heating in the UK

UK domestic energy use by application



Solar thermal systems have application in both space heating and hot water heating

UK – 7% of total energy use on hot water heating alone

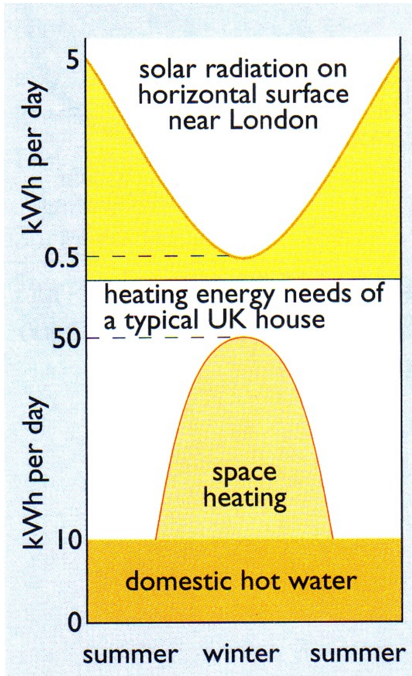
UK – water heated predominantly by burning natural gas

Seasonal Space/Water heating demand

Hot water demand all year round – even in summer when plenty of solar radiation available

Domestic hot water heating best potential application in Europe

UK – estimated that 1kWh of heat from solar thermal will only save 0.19 Kg of CO_2 from being emitted – due to natural gas use
Elsewhere in Europe the figure is nearer to 1 Kg of CO_2 per kWh



Solar Water Heating Systems

Balance of System (BOS) Components

Typical system design involves

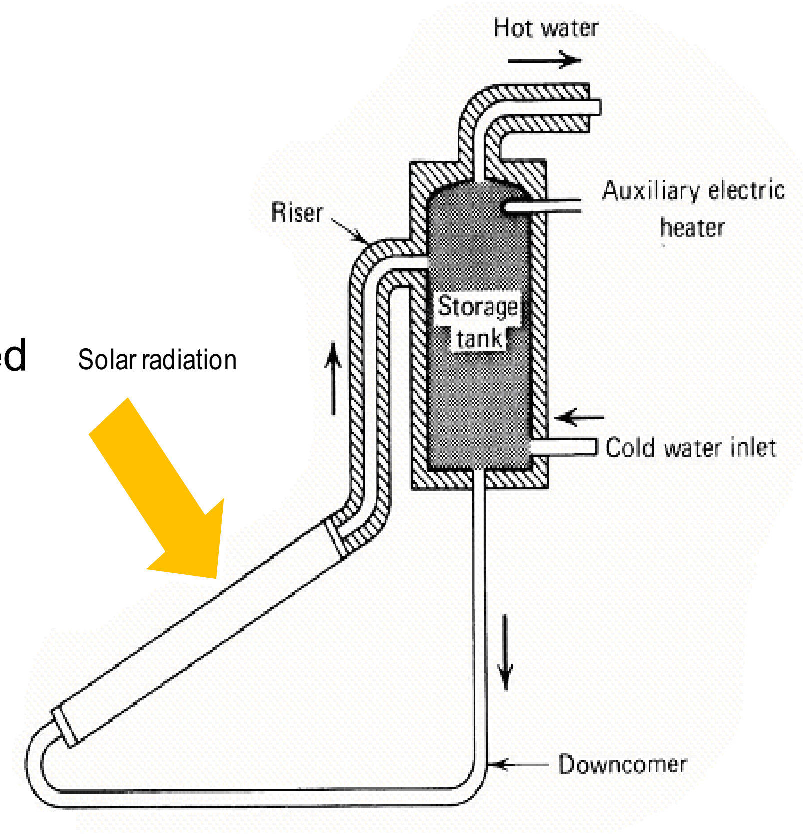
1) Solar Collector – designed to maximize absorption of radiation and minimize heat losses due to radiation

2) Hot Water Storage – Reservoir of heated water is stored until needed at later time (not required in swimming pool applications).

3) Liquid Handling Unit – circulation of heated fluid to storage tank by natural convection (Thermosyphon systems) or forced circulation using a pump.

4) Operator Controller – activate fluid circulation from the collector only when useful heat is available (not required for Thermosyphon systems)

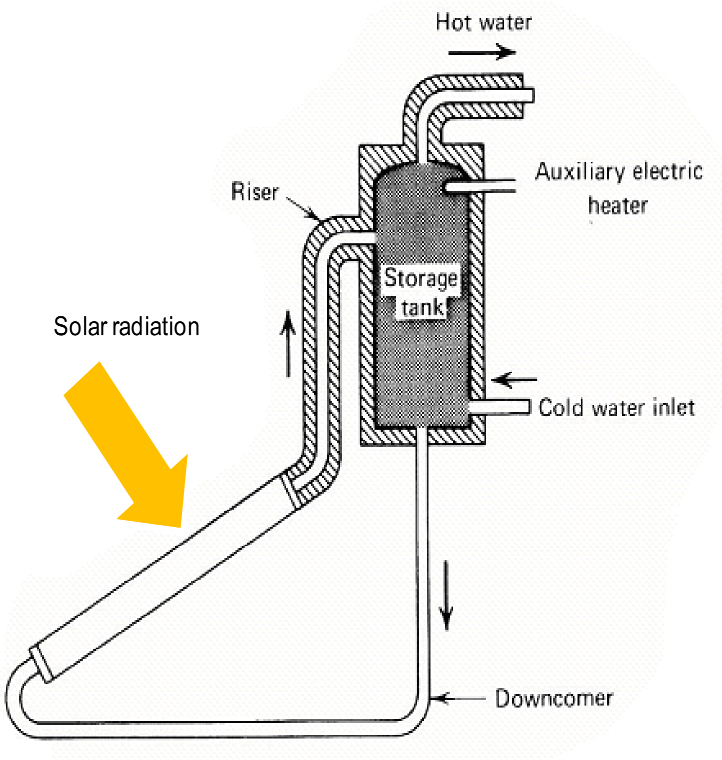
5) Safety system – involving freeze protection for operation during colder months or a heat exchanger circuit

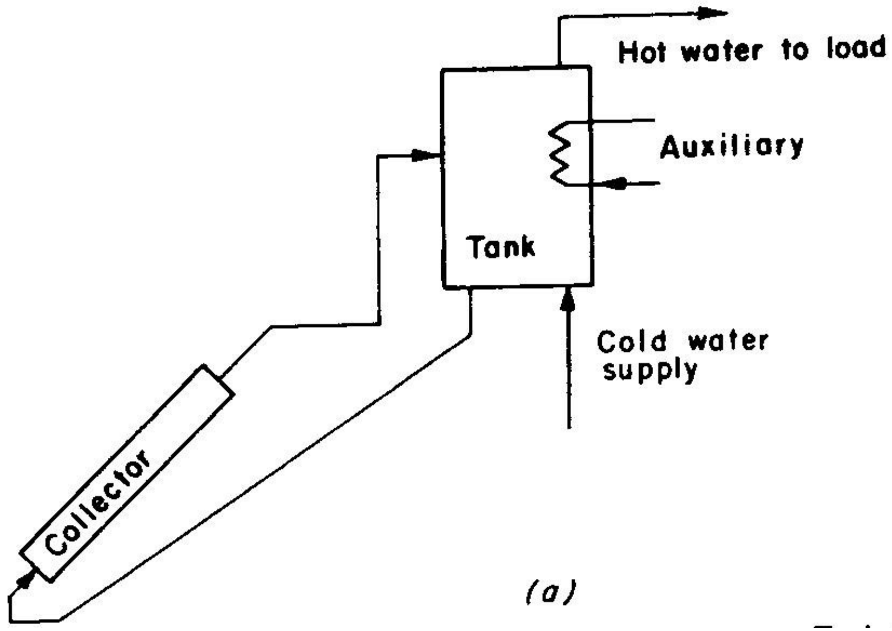


Example of a Solar hot water heater (Thermosyphon system)

Solar Water Heating Systems

Balance of System (BOS) Components





Schematic of Thermosyphon system

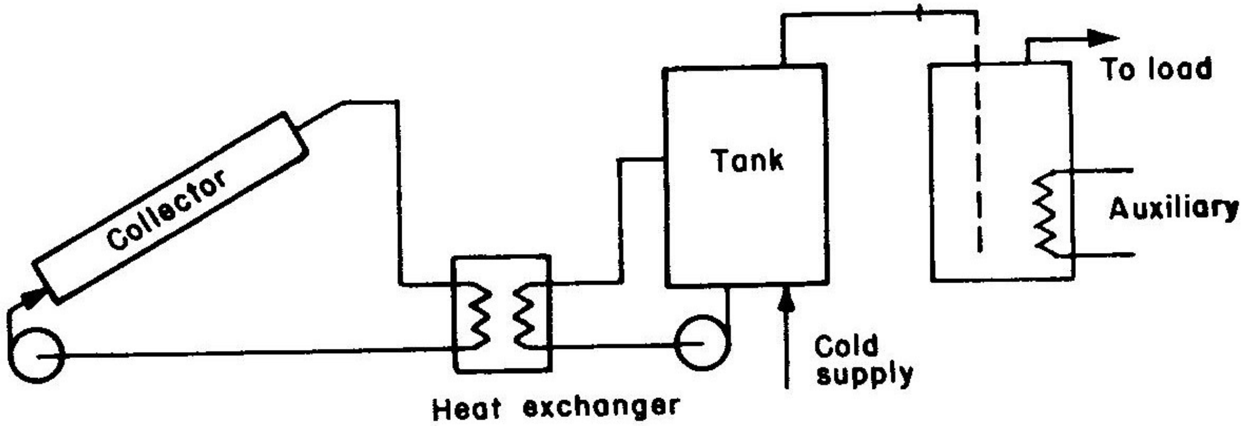
Example of natural convection solar hot water system (Thermosyphon)

Typically used in hot countries for small to medium load applications

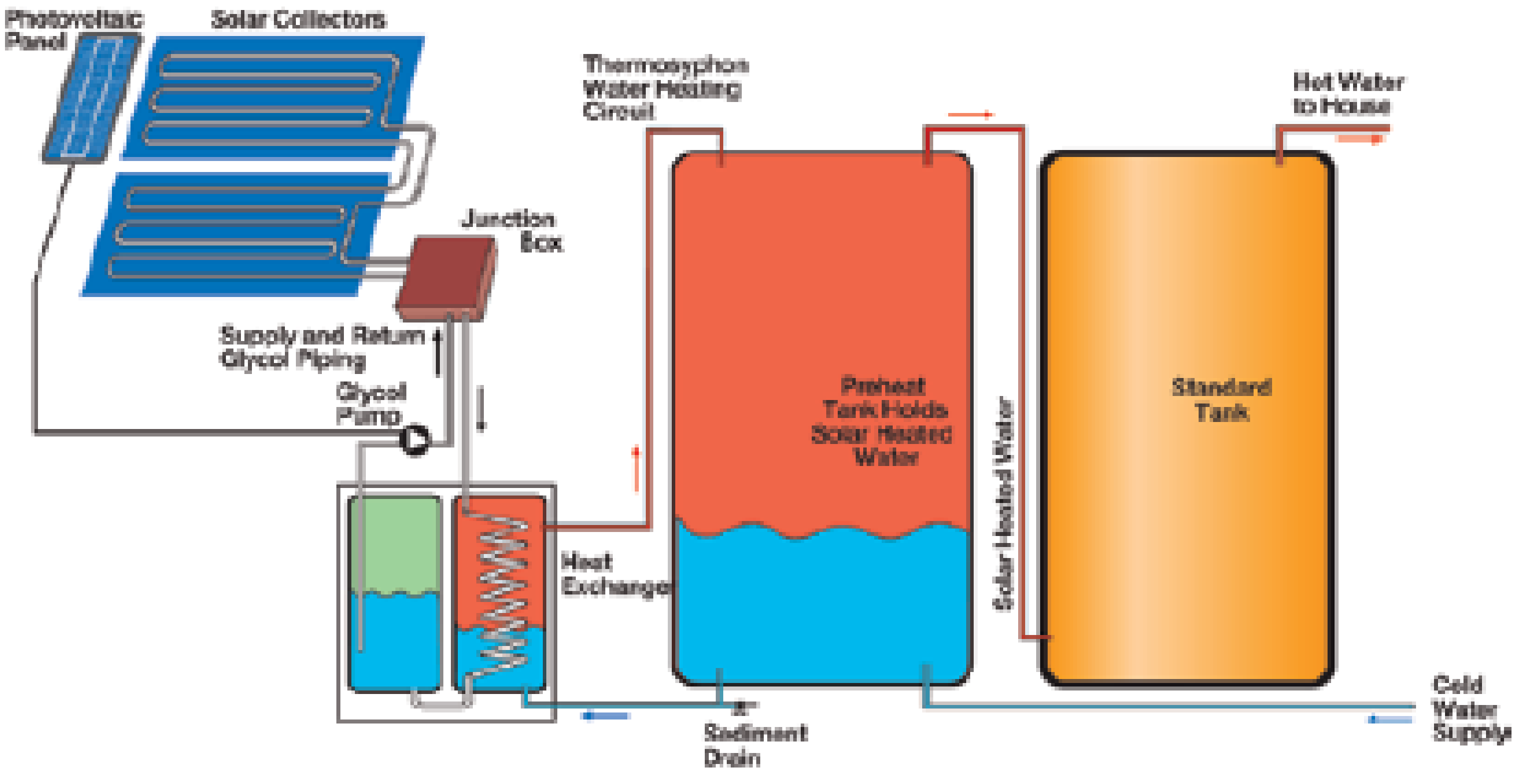
Solar Thermal Energy Systems

Solar Water Heating – Balance of System (BOS) Components

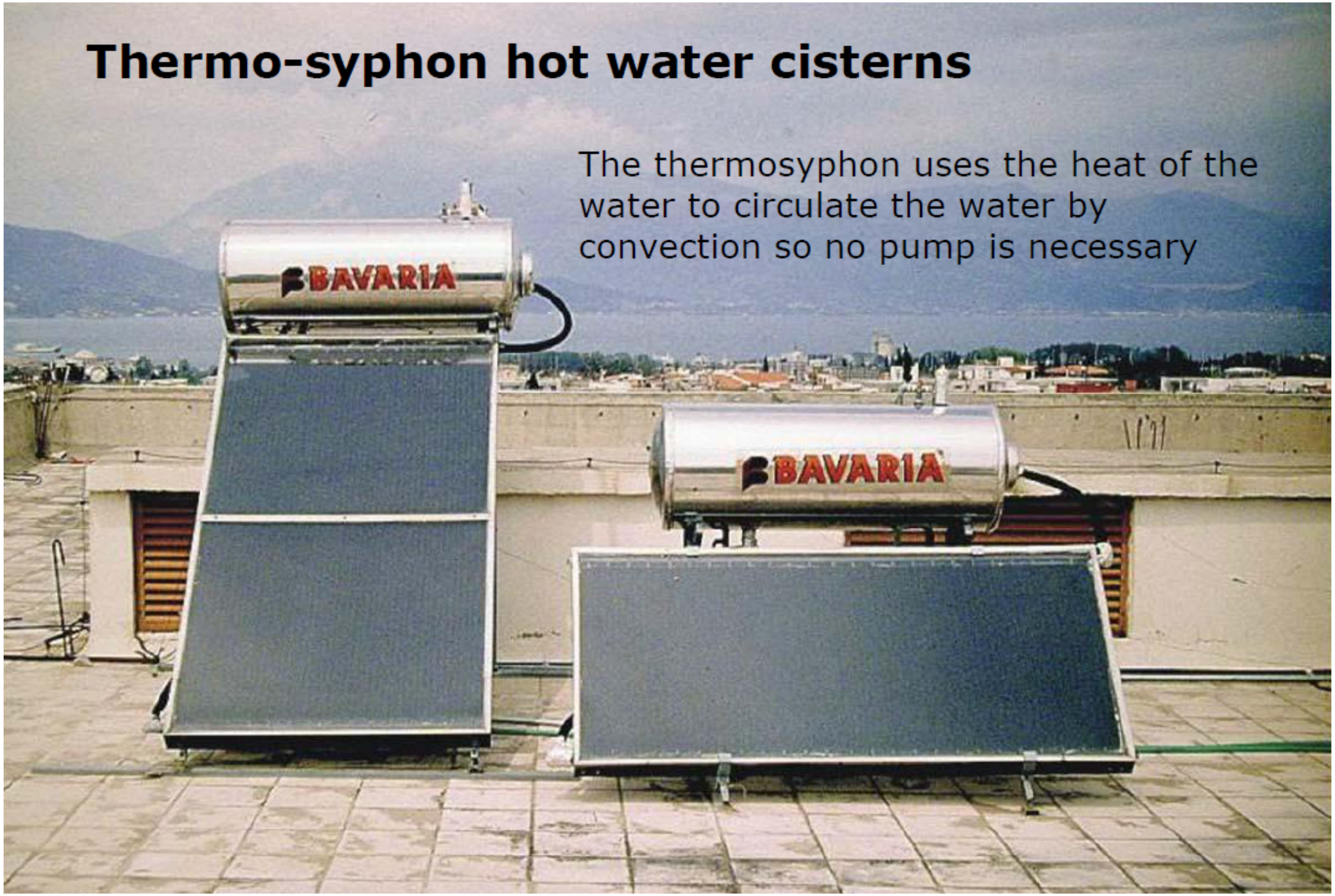
Example schematic of typical domestic solar hot water system – with heat exchanger



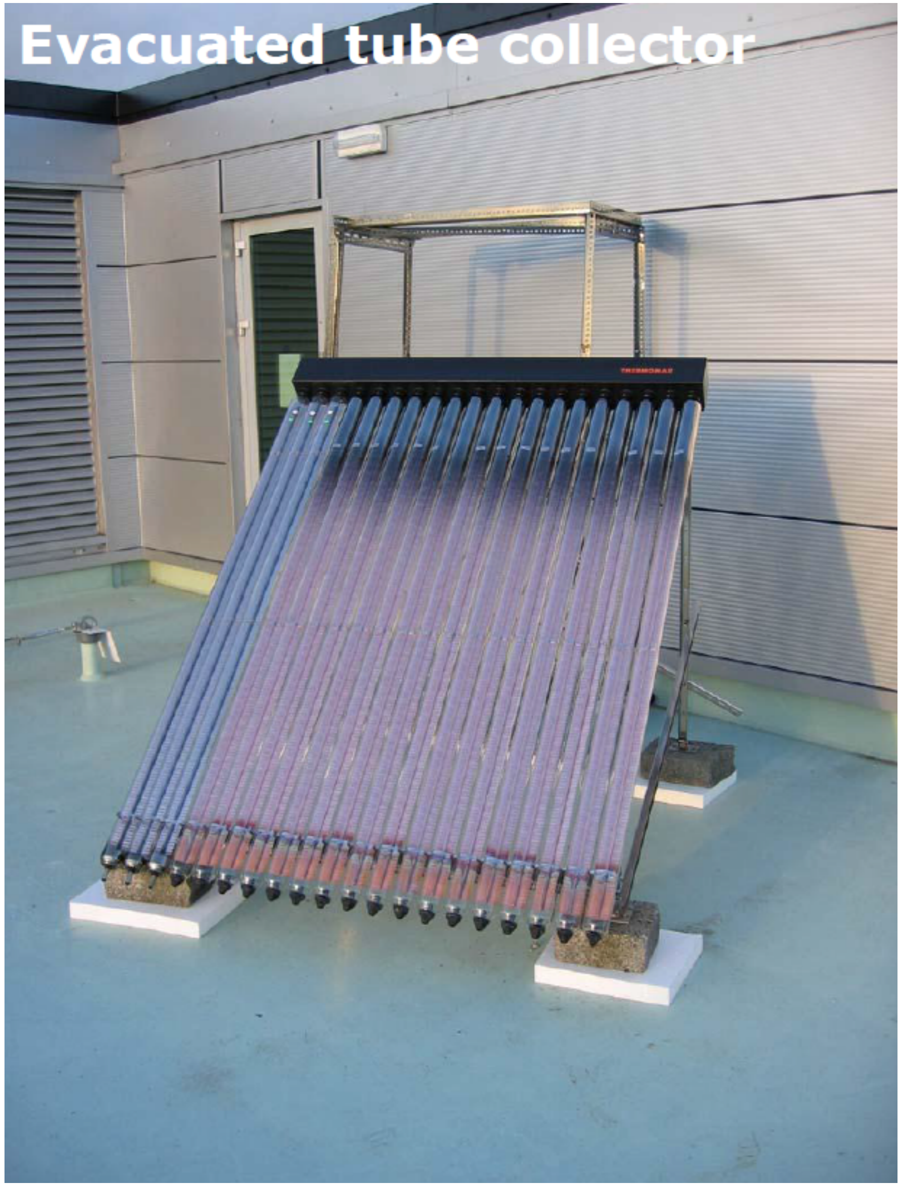
Required in colder countries where freezing may be a problem



Thermo-syphon hot water

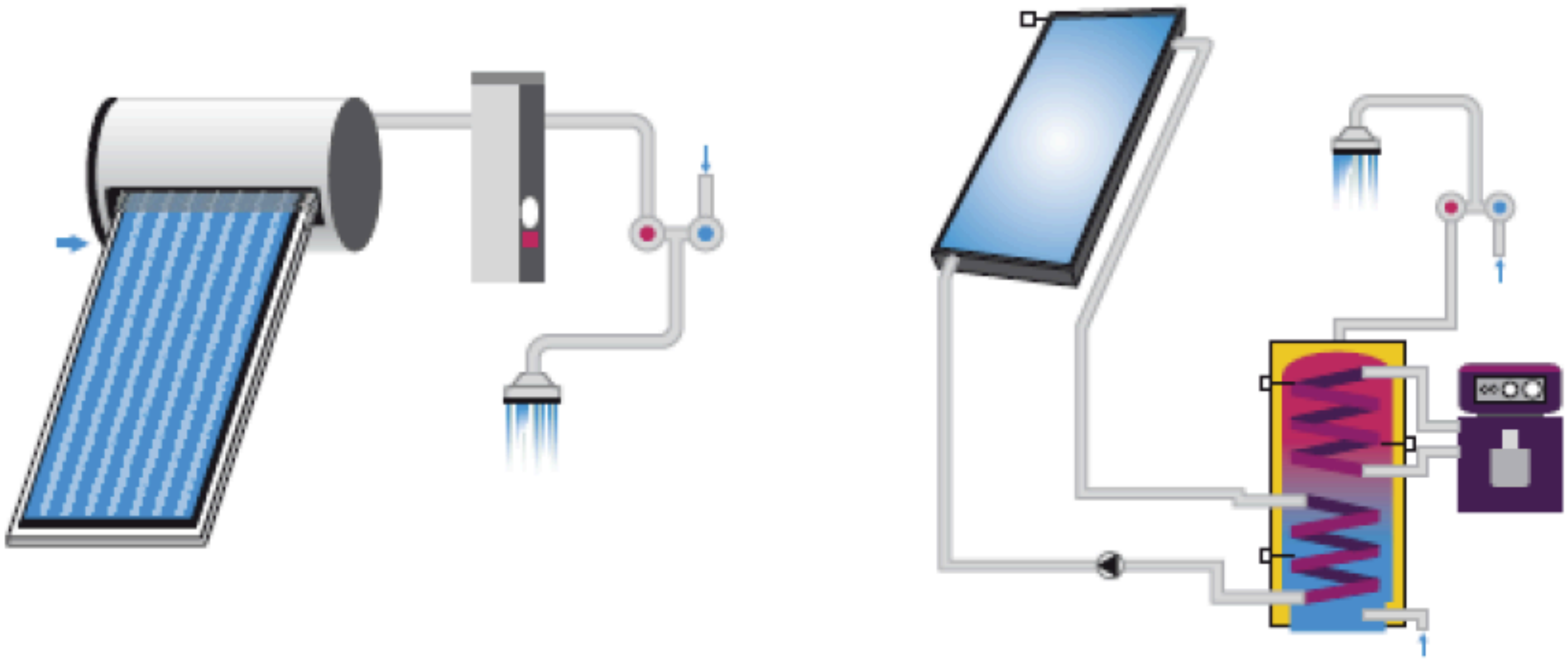


Evacuated tube solar collector



Evacuated tube solar collector

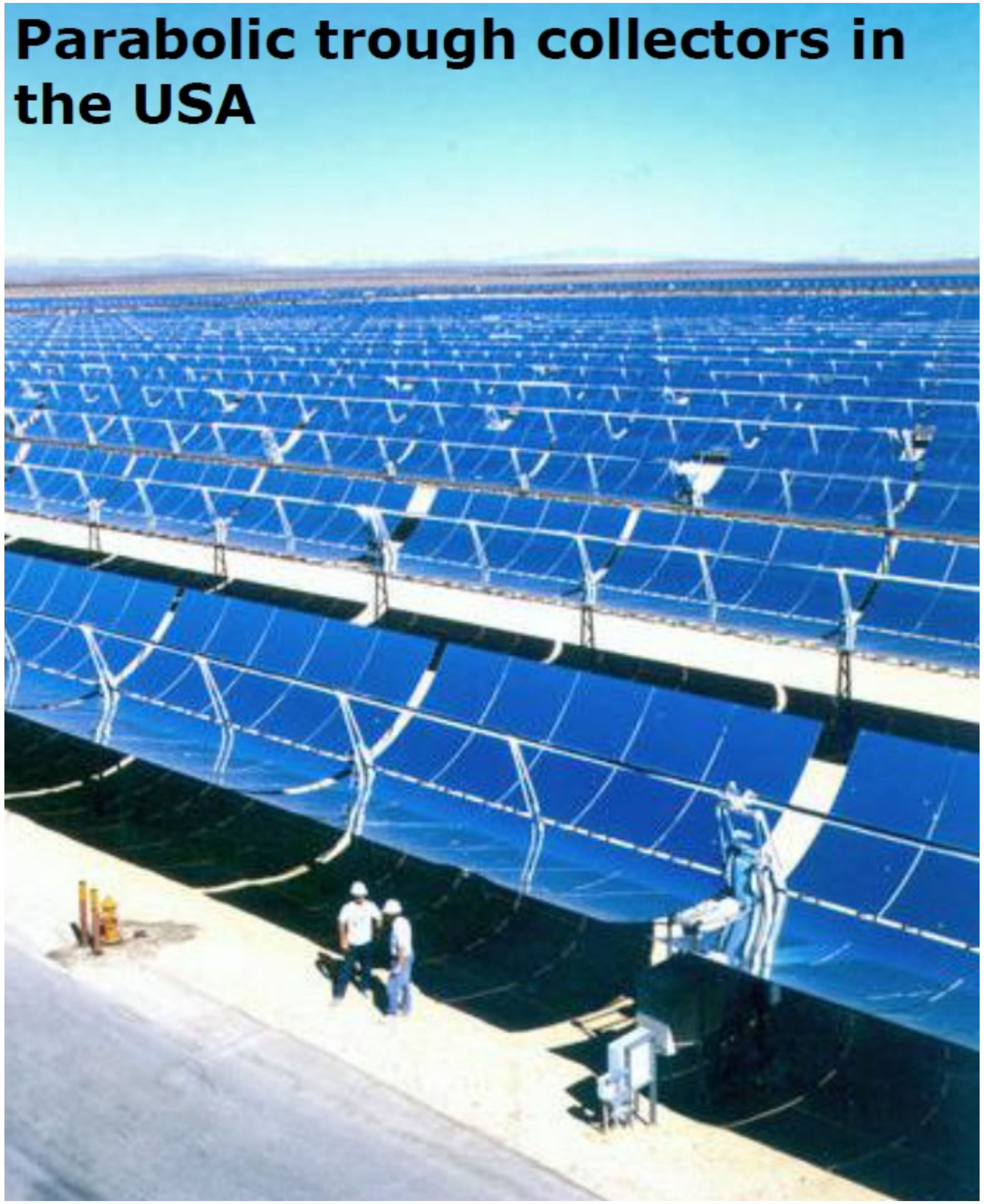
Figure 11. Individual solar thermosiphon system (left) and pumped circulation system (right)



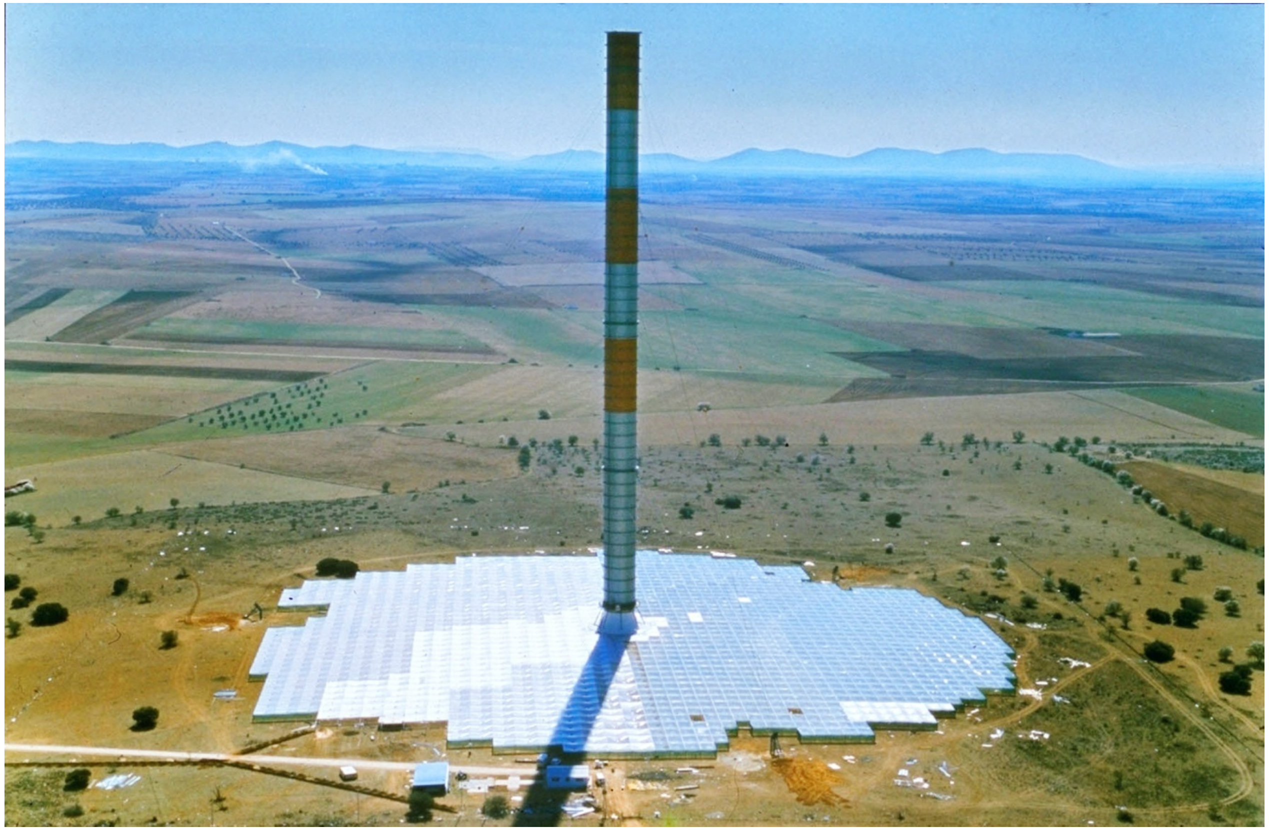
Source: Dr. Valentin Energiesoftware GmbH, reprinted in IEA (2012), *Technology Roadmap: Solar Heating and Cooling*.

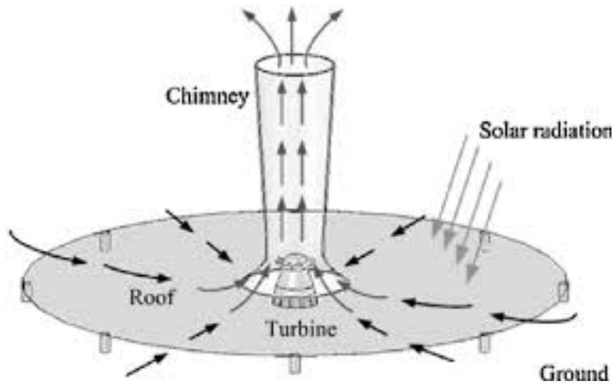
Designs for solar water heating use either natural circulation or a pumping system.

Parabolic trough solar collectors

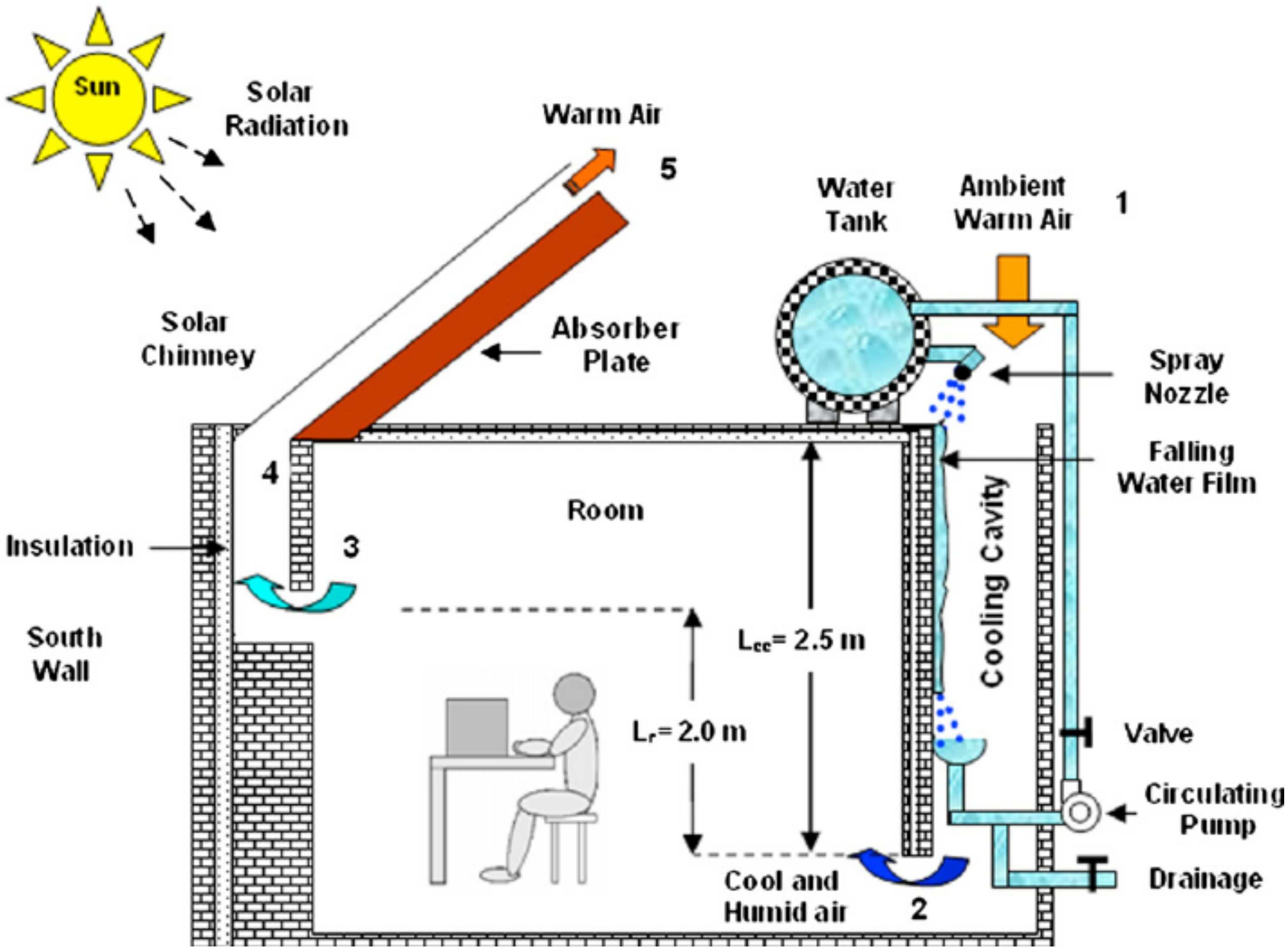


Solar chimney



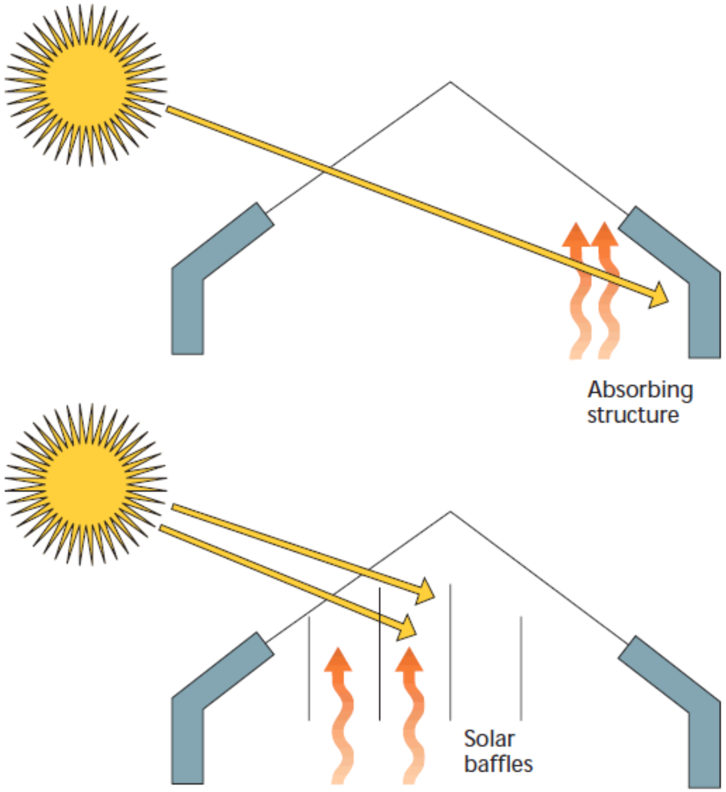


Solar chimney

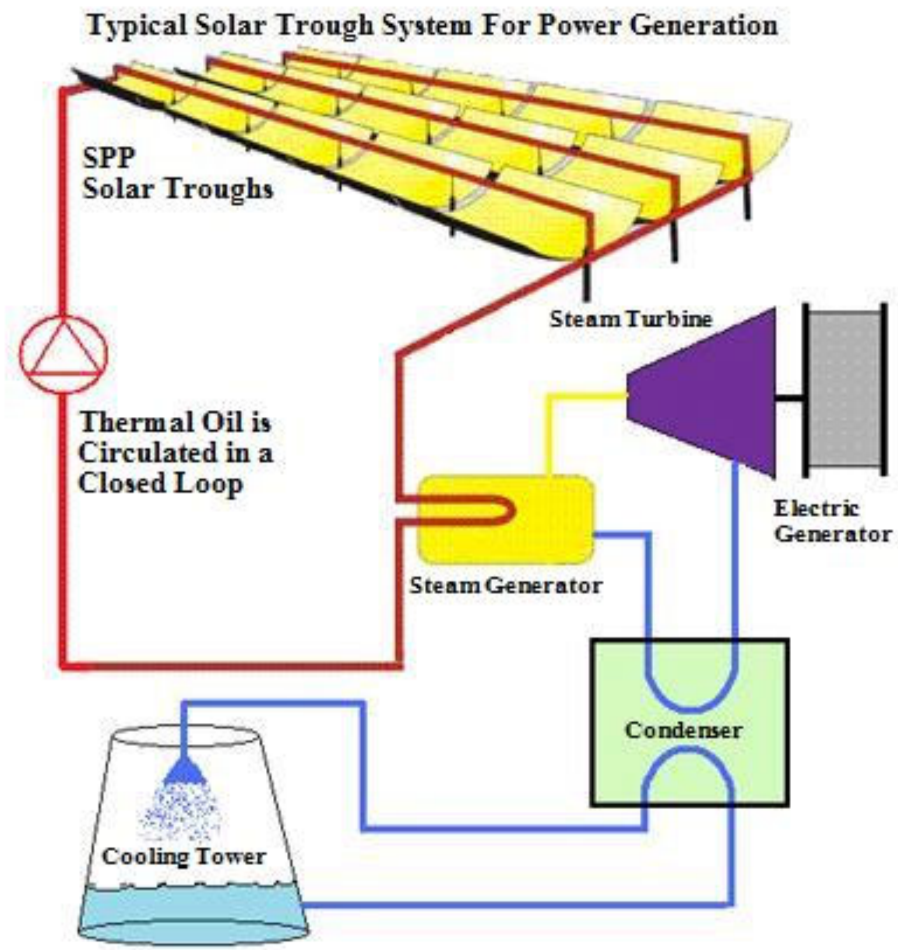


Natural ventilation driven by density difference

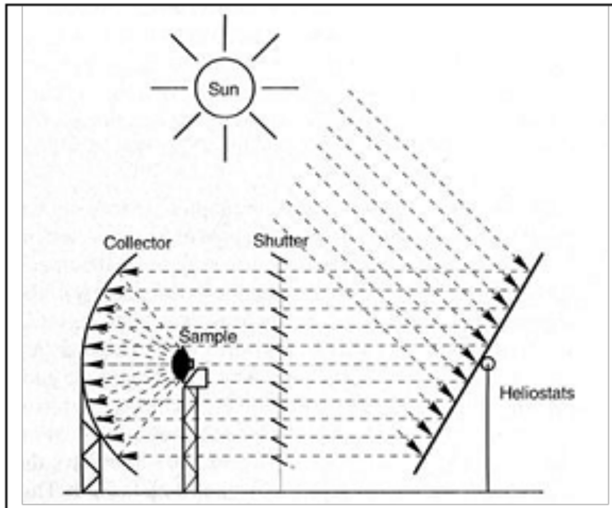
Solar chimneys at BRE's Environmental Builing

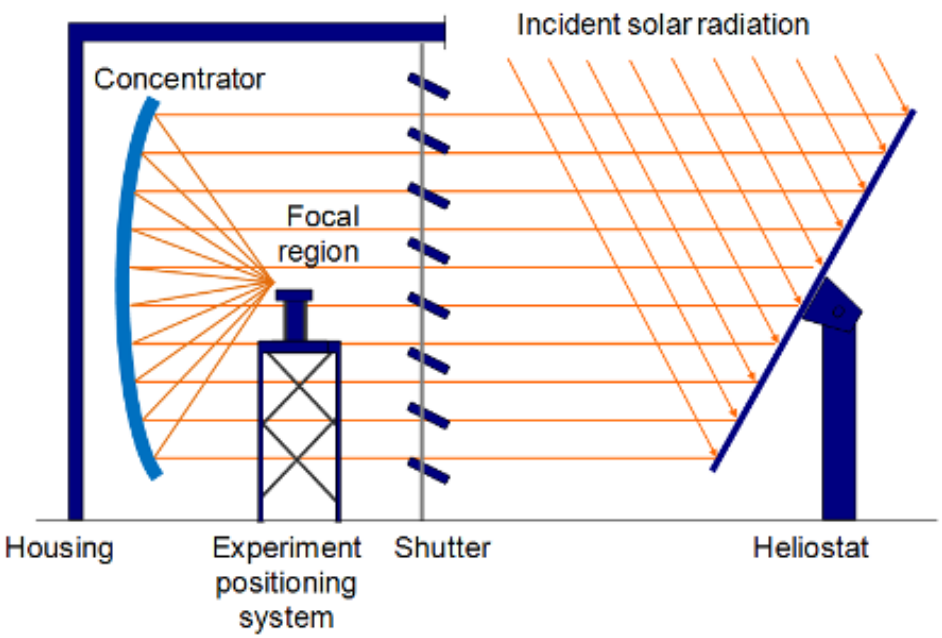


Solar steam power generation



Solar furnace





Design of solar hot water system

Solar Water Heating – 1) Solar Collectors

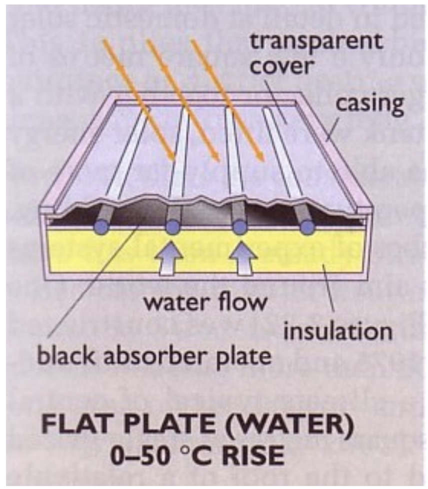
Glazed Flat plate collectors

Flat plate collectors are the simplest and most widely used means of utilizing the sun's radiation for water heating applications.

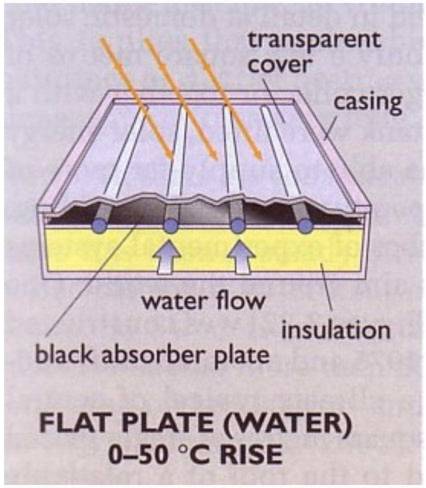
Typical collector system includes:
a) "Black" solar energy absorbing surface with means for transferring absorbed energy to the fluid
b) Transparent glazing over absorber to reduce convective and radiative losses to atmosphere
c) Back insulation to reduce conductive losses

Most commonly used in DHWS to achieve modest temperature rises <50ºC

Example of roof mounted flat-plate collector



Solar Water Heating – 1) Solar Collectors



Function of the glazing

The material must have high transmittance (I_T) to be useful, and therefore the absorptivity (I_A) and reflectivity (I_R) must be minimized

Note: Reflected + transmitted + absorbed = incident

$$I_i(\lambda) = I_R(\lambda) + I_T(\lambda) + I_A(\lambda)$$

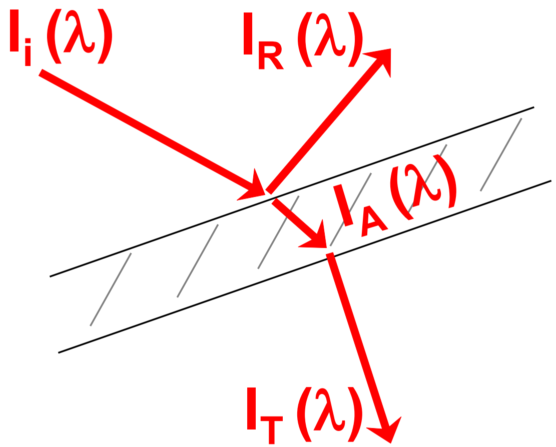
If we define:

$$\alpha_\lambda \equiv \frac{I_A(\lambda)}{I_i(\lambda)} = \text{Spectral absorptance}$$

$$\rho_\lambda \equiv \frac{I_R(\lambda)}{I_i(\lambda)} = \text{Spectral reflectance}$$

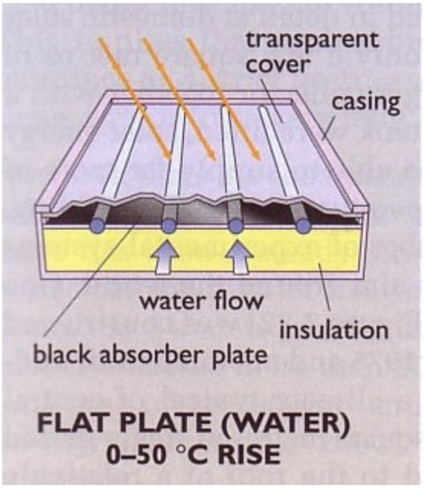
$$\tau_\lambda \equiv \frac{I_T(\lambda)}{I_i(\lambda)} = \text{Spectral transmittance}$$

So, $1 - \alpha\lambda = \rho\lambda + \tau\lambda$



Action of materials on light

Solar Water Heating – 1) Solar Collectors



Function of the glazing

The material must have high transmittance (I_T) to be useful, and therefore the absorptivity (I_A) and reflectivity (I_R) must be minimized

Reflectivity: depends on refractive index and the incidence angle between incoming radiation and line perpendicular to material surface. For a 0° incident angle and a single surface

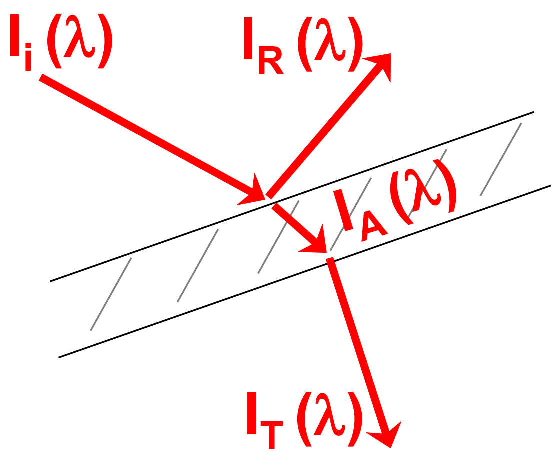
The reflected fraction, $\rho \equiv \left(\frac{n-1}{n+1}\right)^2$

where n is the refractive index of the cover plate material

In the case of glass, which is the most commonly used cover plate material, n = 1.53, and

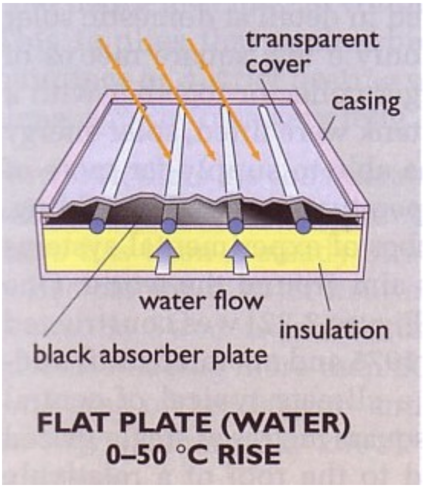
$$\rho \equiv \left(\frac{1.53-1}{1.53+1}\right)^2 \equiv 0.044$$

Therefore, 4.4% of incident radiation is reflected at each surface, and 8.8% is reflected from passage through a single glass sheet



Action of materials on light

Solar Water Heating – 1) Solar Collectors



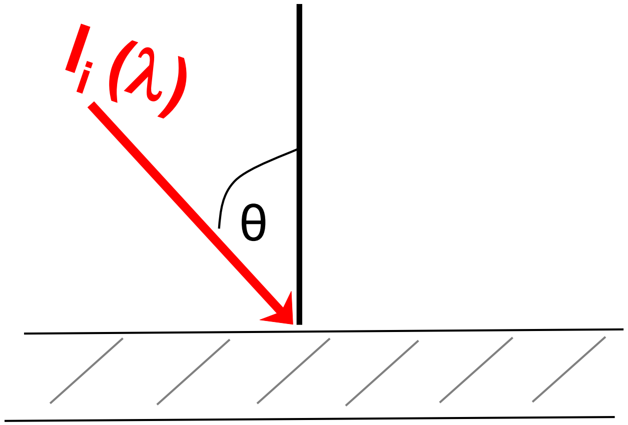
Function of the glazing

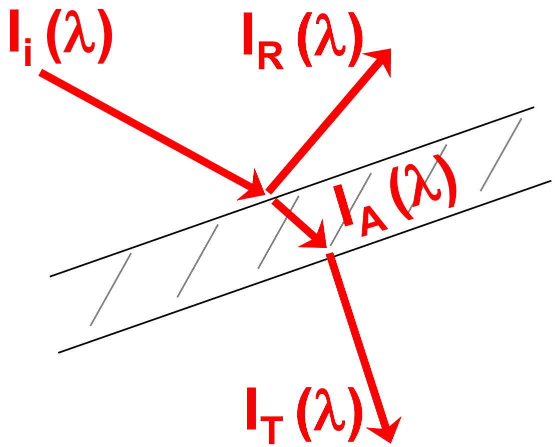
The material must have high transmittance (I_T) to be useful, and therefore the absorptivity (I_A) and reflectivity (I_R) must be minimized

Effect of Incidence angle:

Reflective losses increase with incident angle and reach 18% at 30° on both surfaces

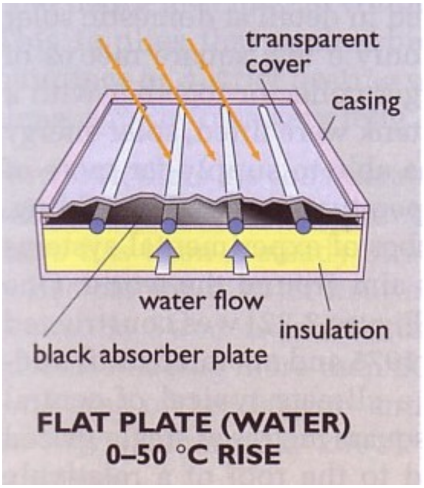
Reflectance can be reduced by use of light-transmitting (anti-reflective) material coatings (ARC), in which case





Action of materials on light

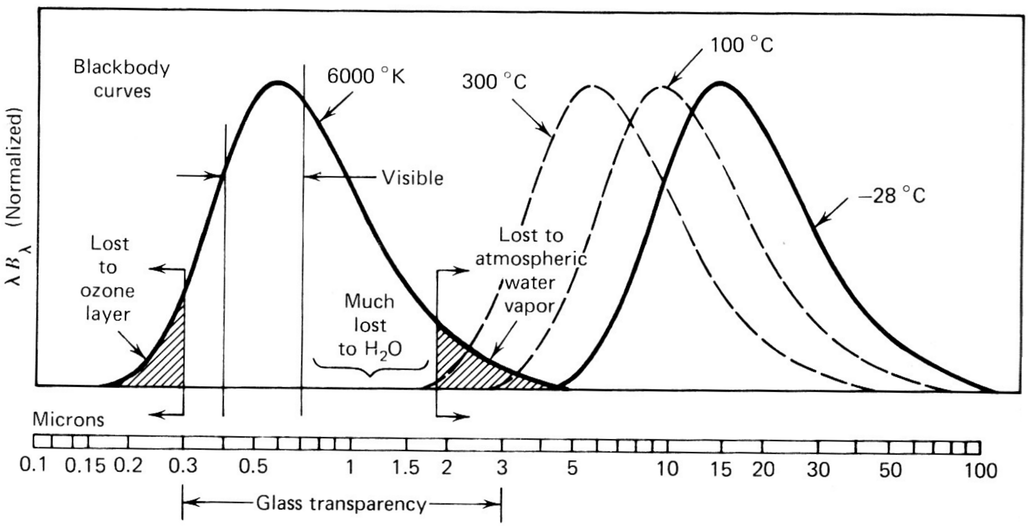
Solar Water Heating – 1) Solar Collectors



Function of the glazing

The material must have high transmittance (I_T) to be useful, and therefore the absorptivity (I_A) and reflectivity (I_R) must be minimized

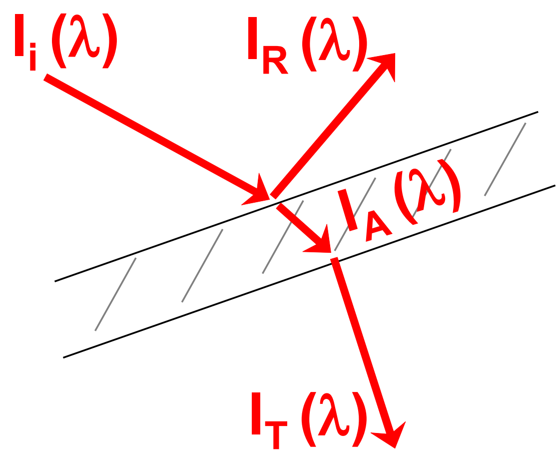
Absorptive properties of glass:



a) Glass allows most of sun's radiation to pass through

b) Absorbs radiated heat from absorber

Reduce radiative losses from absorber – glass heated due to absorption of long-wave radiation so at higher temperature than surroundings Reduce convective losses from absorber



Action of materials on light

Solar Water Heating – Heat Balance

Heat Loss Mechanisms

Heat lost in a number of ways including:

Radiation: from the absorber plate at T_C to the surroundings at T_A

$$Q \equiv 5.673 \varepsilon A \left[\left(\frac{T_H}{100} \right)^4 - \left(\frac{T_L}{100} \right)^4 \right] \qquad (1)$$

where T_H and T_L are the absolute temperatures (kelvin) of the hot and cold objects respectively and ε is the emissivity of the surface.

Conduction: Objects in contact transmit heat to each other
Fourier heat transfer equation:

$$Q \equiv \frac{kA\Delta T}{L} \qquad (2)$$

where *k* is the thermal conductivity of material and L the thickness of material

Convection: Heat transfer to surrounding gas or liquid. Heated fluid becomes less dense and rises being replaced by cold fluid and the process is repeated in a circulating flow. Convective heat transfer described by

$$Q \equiv hA\Delta T \qquad (3)$$

Solar Water Heating – Heat Balance

Solar Water Heating Applications

To simplify the relationship a combined overall heat-transfer coefficient U_L is used so that

$$Q_L = A_C U_L (T_C - T_A)$$

Typical U_L value for a glazed collector is 5.00 W/m^2 K

Combining heat gain and heat loss terms gives

$$Q_C = A_C(\tau+\alpha)G - A_C U_L(T_C - T_A)$$

Here Q_c is the energy collected and G is the incoming energy flux.

Dividing by A_C, to express as heat flux per unit area of collector gives

$$q_C = (\tau+\alpha)G - U_L(T_C - T_A) \qquad (4)$$

Example Tutorial Problem

Example analysis

As in a previous example, let us consider the situation on 21st November (day 325) at a site latitude of 40ºN

The solar declination, sunset angle and the length of the solar day were previously calculated to be:

Solar declination, $\delta \equiv 23.45^\circ \sin\left[\left(\frac{325-80}{370}\right)\times 360\right] \equiv -20^\circ$

Sunset angle, $\omega_s \equiv \cos^{-1}\left(-\tan(40^\circ)\tan(-20^\circ)\right) \equiv 72.22^\circ$

Length of solar day, $\omega_s \equiv \frac{\pm 24}{360} \times \omega_s \equiv \pm 4.81\,\mathrm{h}$

Therefore, number of hours sun is above horizon = 2 x 4.81 = 9.62 h

Example Tutorial Problem

Example analysis

The variation in extraterrestrial radiation throughout the day on a horizontal surface can be calculated using

$$H_o \equiv I_o(\cos\phi\cos\delta\cos\omega + \sin\phi\sin\delta)$$

Which for example at 10A.M. (-2 h from solar noon) is found to be

$$H_o \equiv 1392(\cos(40^\circ)\cos(-20^\circ)\cos(-30^\circ) + \sin(40^\circ)\sin(-20^\circ)) \equiv 552\ \mathrm{Wm^{-2}}$$

Assuming a clearness index, K_T of 0.6 the solar radiation received at ground level on a horizontal collector is calculated as follows:

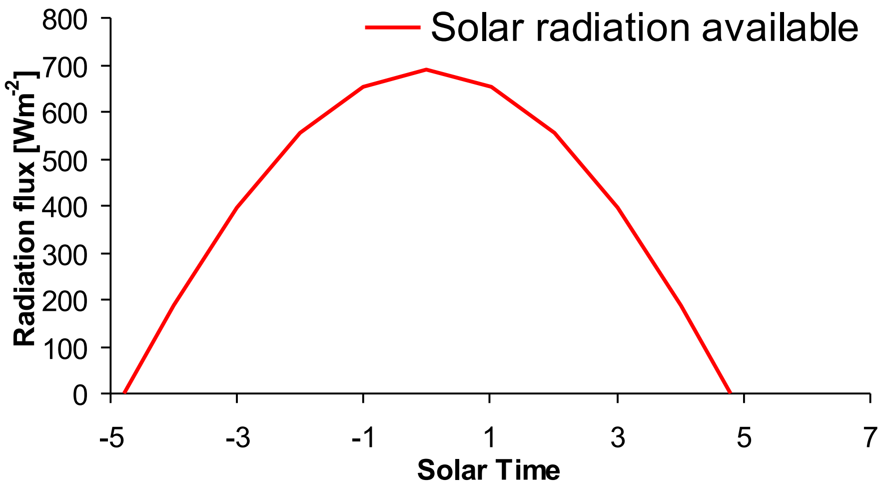
$$G \equiv K_T \times H_o \equiv 0.6 \times 552 \equiv 332\ \mathrm{Wm^{-2}}$$

The diffuse, beam and reflected components falling on a collector panel inclined at 30º to the horizontal can now be found to give the global radiation on the inclined surface throughout the day

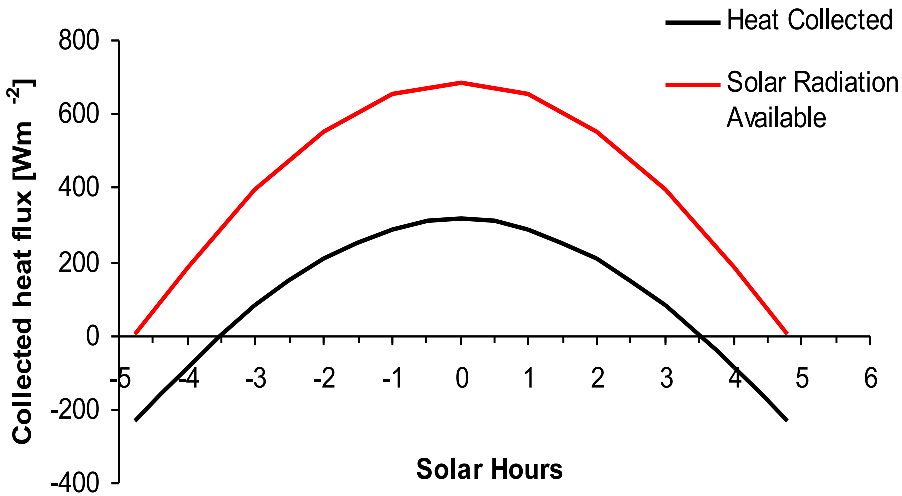
Example Tutorial Problem

Example analysis

The variation in available solar radiation throughout day 325 at a latitude of 40ºN on a panel inclined 30º to the horizontal



Assuming the optical efficiency ($\tau+\alpha$) to be 0.8 and the heat loss coefficient for the collector to be 5.2 Wm^{-2} K and ambient and collector temperature to be 5 and 50 ºC respectively, we can calculate the heat flux collected throughout the day



$$q_C = (\tau+\alpha)G - U_L(T_C - T_A) \qquad (4)$$

Solar Thermal Collector Efficiency

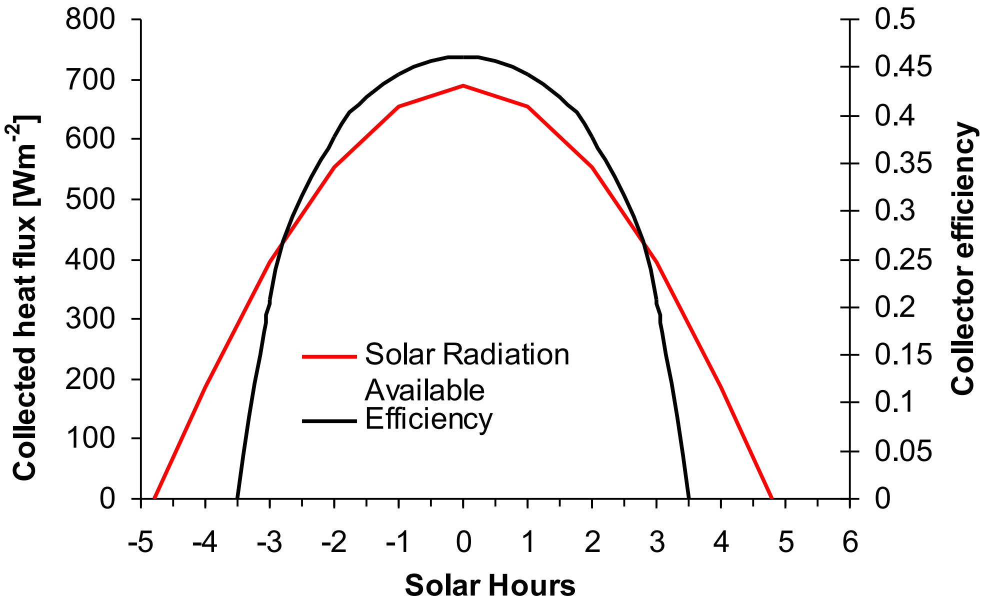
The collector efficiency, η is the ratio of the amount of heat collected to that available

$$\eta \equiv \frac{q}{G}$$

If equation (4) is divided by *G* the efficiency can be expressed as

$$\eta \equiv \tau + \alpha - U_L\left(\frac{T_C - T_A}{G}\right) \qquad (5)$$

We can now calculate the collector efficiency during the day of interest

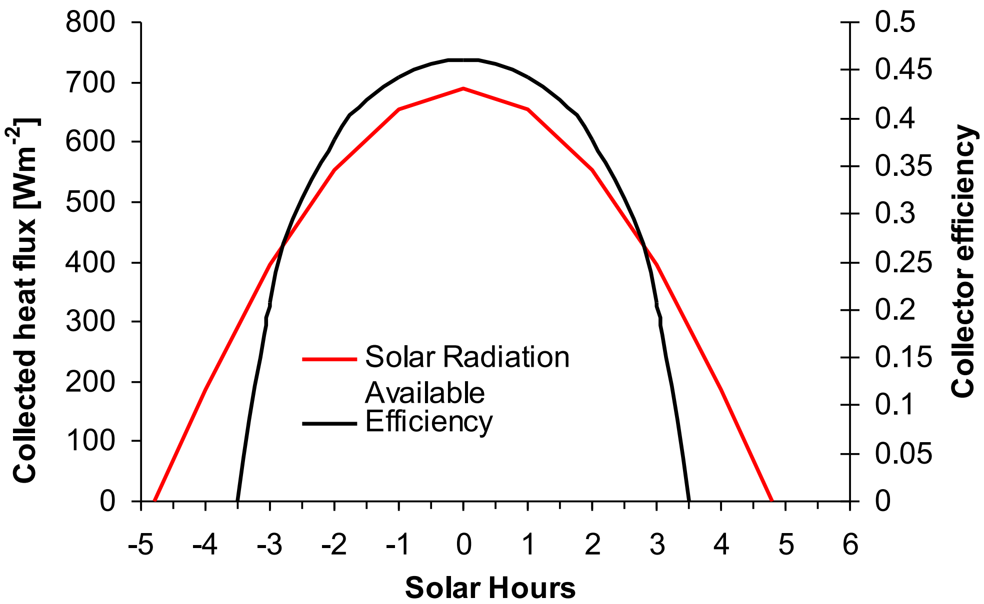


Note: When collector efficiency is negative the radiation flux cannot make up for heat losses and the collector should not be operated

Solar Thermal Threshold Radiation

As seen from the plot below, there is a **minimum** radiation level needed before heat can be collected called the *threshold radiation level, I_{th}*

The collector will have zero efficiency as it begins to deliver heat and equation (5) can be rearranged to calculate the threshold radiation level as follows :



$$0 \equiv \tau + \alpha - U_L \left(\frac{T_C - T_A}{G} \right)$$

Therefore, by substituting relevant values the threshold radiation is found as:

$$I_{th} \equiv \frac{U_L (T_C - T_A)}{\tau + \alpha} \equiv 292.5 \text{ Wm}^{-2}$$

Solar Thermal Operation Performance

In the case of an operating collector, the mass flow rate is no longer zero and heat is carried away from the absorber by the fluid

In this case the outgoing temperature of the fluid $T_{c.out}$ will be higher than the inlet temperature $T_{c.in}$

$$Q \equiv Wc(T_{\text{c.out}} - T_{\text{c.in}}) \tag{6}$$

Considering the situation at solar noon with an average collector temperature of 50 ºC and a mass flow rate of water of 0.01 (kg s^{-1}) and the heat capacity of water is 4.19 (kJ/kg K) what will be the temperature gain if the inlet water temperature is 40 ºC and the collector area is 4 m^2

$$Q_{Tot} \equiv A_C \times q_C \equiv (\tau + \alpha)G - U_L(T_C - T_A)$$

$$Q_{Tot} \equiv 4 \times 316 \text{ W} \equiv 1.264 \text{ kW} \equiv 1.264 \text{ kJs}^{-1}$$

Rearranging Eq. (6) and inputting values gives

$$T_{\text{c.out}} = \frac{Q_{\text{Tot}}}{Wc} + T_{\text{c.in}} = \frac{1264}{0.01 \times 4190} + 40 = 70.1\,^{\circ}\text{C}$$

Solar Thermal Energy – Integrated equation

Much more useful to predict the operation over the whole day

This can be done using an integrated heat storage equation and assuming well mixed storage. The total energy gained over a certain time period t_T can be predicted using the following

$$q_T = \frac{[\overline{(\tau + \alpha)}G_T - U_L(T_{s0} - \bar{T}_a)t_T]}{1 + \frac{U_L t_T}{2mc}} \qquad (7)$$

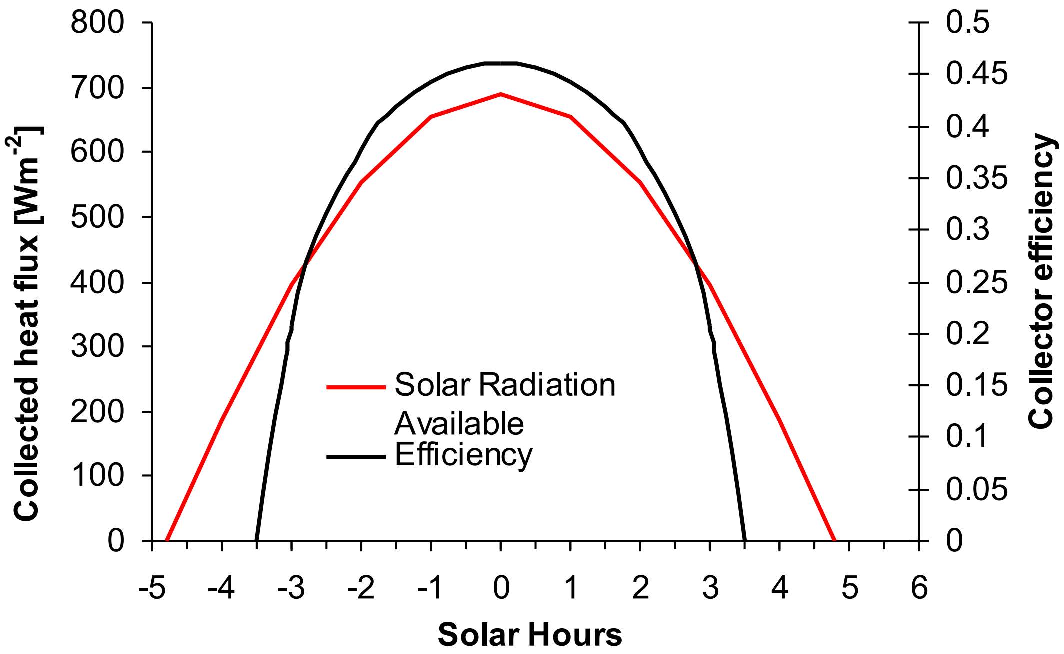
where G_T is the total radiation received over the time period and m is the mass of liquid in storage divided by the collector area and c is it's heat capacity (heat capacity of water is 4.19 kJ/kg K). This gives the energy gained as per unit collector area

The temperatures T_a, T_{s0} and T_{sf} are the average ambient, the initial storage and the final storage temperatures respectively and

$$T_{sf} = T_{s0} + (\frac{q_T}{mc}) \qquad (8)$$

Solar Thermal Threshold Radiation

Considering the situation in our example of day 325 at 40°N



Time	G (W/m^2)	Efficiency	Useful Energy
8 A.M	187.4	-0.45	----
9 A.M.	394.7	0.21	394.7
10 A.M.	553.7	0.38	553.7
11 A.M.	653.7	0.44	653.7
Noon	687.8	0.46	687.8
1 P.M.	653.7	0.44	653.7
2 P.M.	553.7	0.38	553.7
3 P.M.	394.7	0.21	394.7
4 P.M.	187.4	-0.44	----
Total			**3892 Wh/m^2**

Therefore the total radiation G_T = 3892 Wh/m^2 (over 7 hours)

Example Problem

Predict the temperature increase of stored water if the initial temperature is 40 °C, mc for the system is 0.2044 MJ/m^2 K, U_L is 5.2 W/m^2 K, the average ambient temperature over the day is 5 °C

Solar Thermal Threshold Radiation

Considering the situation in our example of day 325 at 40°N

Time	G (W/m²)	Efficiency	Useful Energy
8 A.M	187.4	-0.45	----
9 A.M.	394.7	0.21	394.7
10 A.M.	553.7	0.38	553.7
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Total			**3892 Wh/m²**

Example Problem
Predict the temperature increase of stored water if the initial temperature is 40 °C, mc for the system is 0.2044 MJ/m² K, U_L is 5.2 W/m² K, the average ambient temperature over the day is 5 °C

First use equation (7)

$$q_T = \frac{[\overline{\tau\alpha}G_T - U_L(T_{s0} - \overline{T}_a)t_T]}{1 + \frac{U_L t_T}{2mc}}$$

Therefore the total radiation G_T = 3892 Wh/m² (over 7 hours)

$$q_T = \frac{[(0.8 \times 3892) - (5.2(40-5) \times 7)] \times 0.0036}{(1 + (\frac{5.2 \times 7 \times 0.0036}{2 \times 0.2044})} = 4.99 \,\mathrm{MJ\,m^{-2}}$$

So total energy added to storage over the day is 4.99 MJ/m²

Solar Thermal Threshold Radiation

Considering the situation in our example of day 325 at 40°N

Time	G (W/m²)	Efficiency	Useful Energy
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4 P.M.	187.4	-0.44	----
Total			**3892 Wh/m²**

Therefore the total radiation G_T = 3892 Wh/m² (over 7 hours)

Example Problem

Predict the temperature increase of stored water if the initial temperature is 40 °C, *mc* for the system is 0.2044 MJ/m² K U_L is 5.2 W/m² K the average ambient temperature over the day is 5 °C

Then calculate the temperature rise from

$$T_{sf} = T_{s0} + \left(\frac{q_T}{mc}\right)$$

giving

$$T_{sf} = 40 + \left(\frac{4.99}{0.2044}\right) = 64.4°C$$

So final temperature of stored water is 64 °C

Note: Process more accurate the shorter the time period – iterative procedure