# RENEWABLE ENERGY SOLAR THERMAL ENERGY

*Professor Nasr Ghoniem*

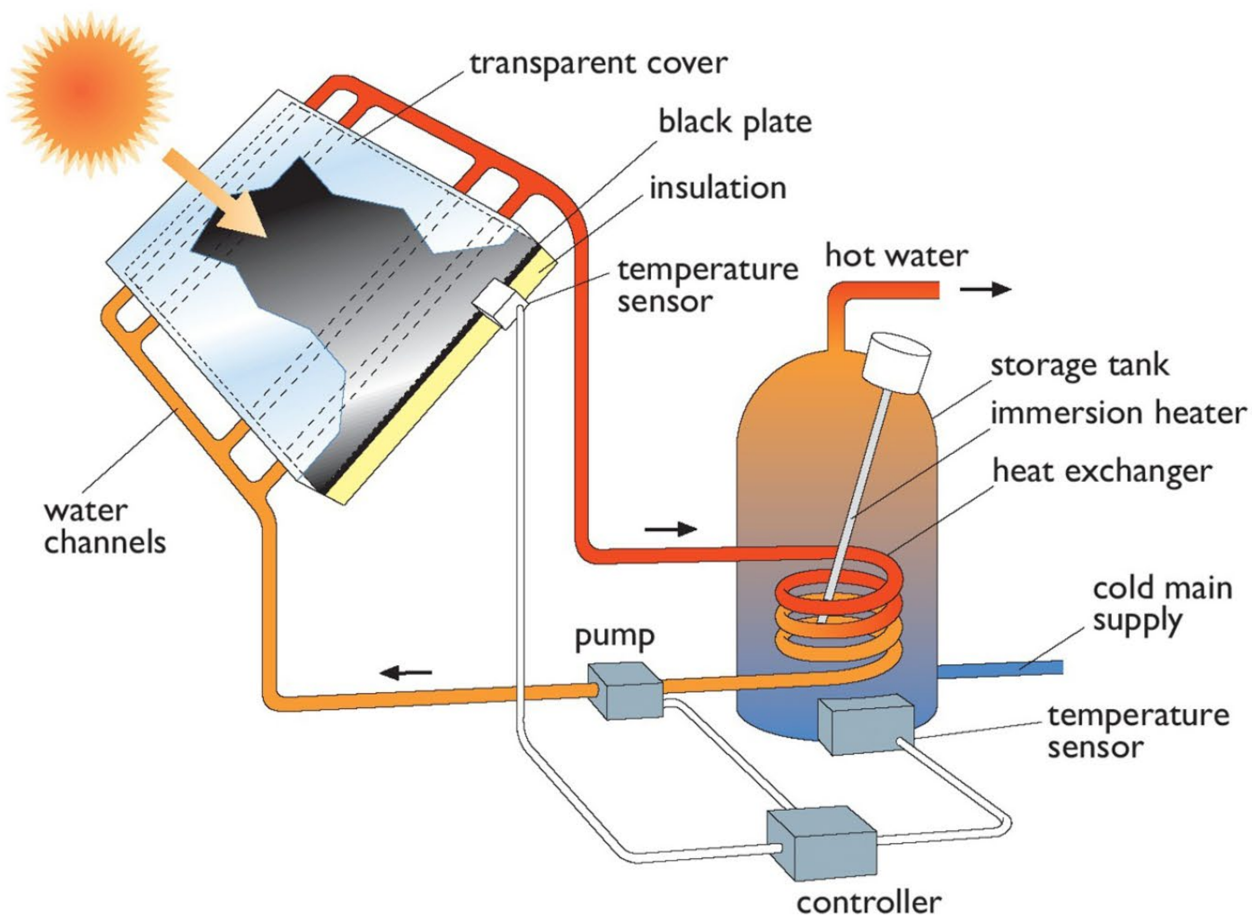
*UCLA*

# LECTURE OUTLINE

- The rooftop solar water heater
- The nature and availability of solar radiation
- Glass properties
- Low-temperature solar energy applications
- Active solar heating
- Passive solar heating
- Daylighting
- Solar thermal engines and electricity generation
- Solar thermal process steam

# *Solar Water Heater*

# The pumped solar water heater



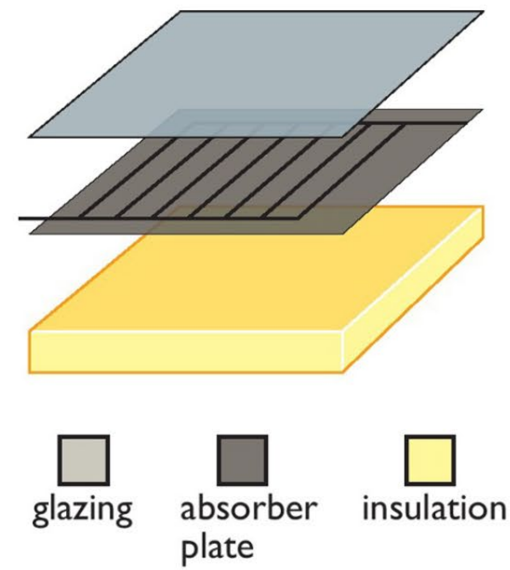




**Figure 3.3** Components of a solar panel

The thermo-syphon relies on the natural convection of hot water rising from the collector panel to carry heat up to the storage tank, which must be installed above the collector.

# *Solar Radiation*

# *Black Body Radiation*

**Planck's Law:** Describes the dependence of radiation intensity on the wavelength.

**Wien's Displacement Law:** The peak wavelength is inversely proportional to the wavelength.

$\lambda_{max}$=2.898x$10^{-3}$ /T    $\lambda$ is in [m], and T in [K]

**Stefan-Boltzmann Law:** The radiated energy per unit surface area is proportional to the fourth power of its temperature

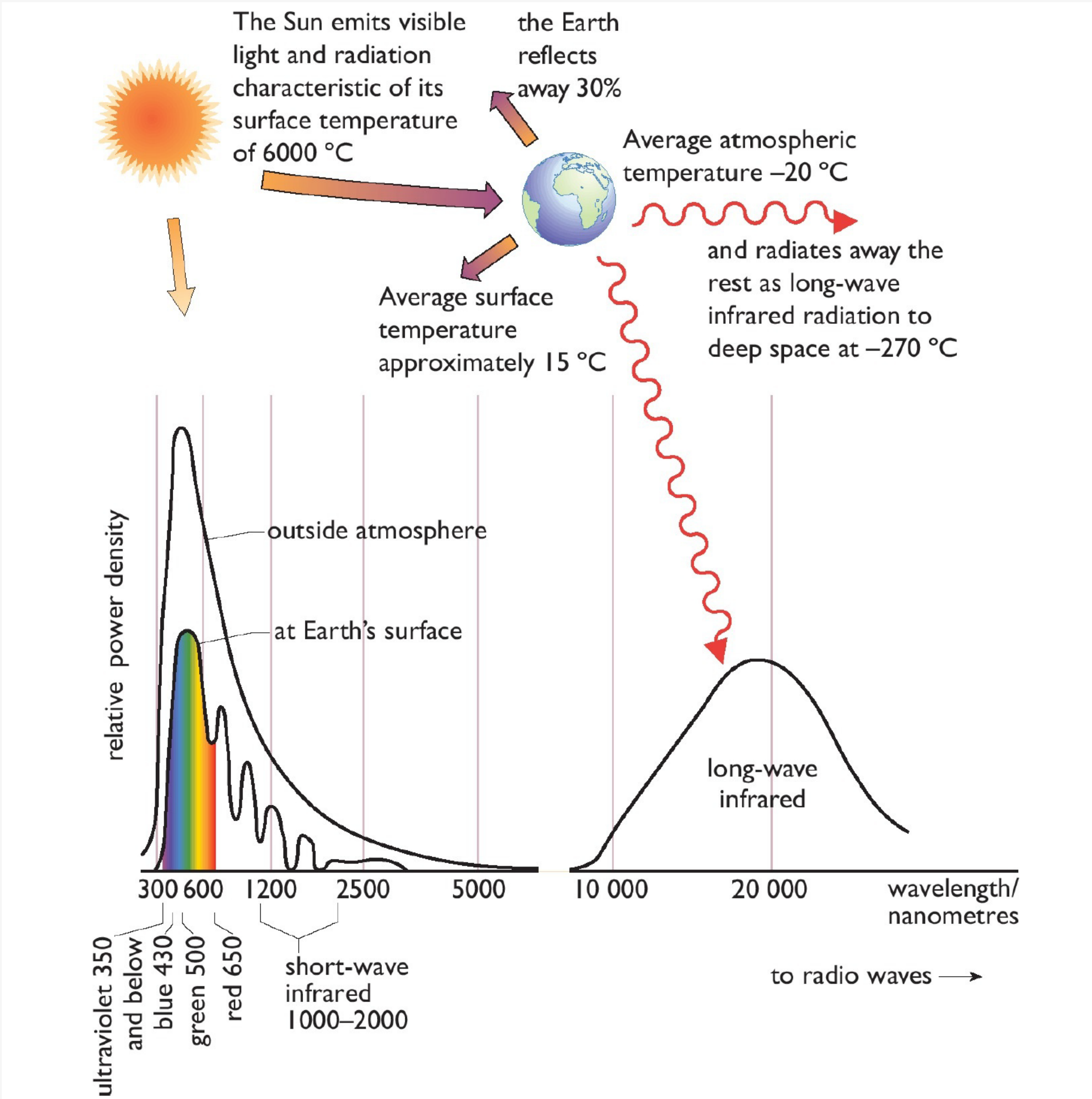
$$P=\sigma T^4$$

**Planck's Hypothesis:** Energy is emitted in discrete units called "photons'. This laid the foundations for quantum mechanics.

$E=h\nu=hc/\lambda$    E= energy, $\lambda$=photon wavelength [m]

h=Planck's constant= 6.626X$10^{-34}$ J.s
$\nu$=photon frequency (Hz)    c=speed of light=3x$10^{8}$ m/s

# Solar Radiation Spectrum



# Definitions

- Active solar heating - using solar collectors
- Passive solar heating –using solar energy directly into buildings for space heating (or to heat the interior spaces).
- Daylighting involves making the best use of natural daylight in buildings to avoid the use of artificial lighting.
- Solar thermal engines use solar thermal heat to generate electricity, mostly by the use of concentrating solar collectors.

# Definitions

- Rooftop solar water heaters are used to supply domestic hot water. There are two basic types:

- The pumped solar water heater uses a roof-mounted solar collector above a hot water storage tank, usually located inside the building.

- The thermosyphon solar water heater has the storage tank mounted above the solar collector and uses natural convection to circulate water between the two.

# *Definitions*

**Direct radiation**, the unobstructed rays of the Sun, is important for concentrating collectors.

**Diffuse radiation**, light from the Sun reflected from the clouds or the sky is important for natural lighting and can be collected by both active and passive solar thermal systems.

**Glass and other plastic glazing materials**, have the ability to transmit light but block the re-radiation of long-wave infrared radiation (heat).

There are three basic mechanisms of heat loss through a double glazed window: *conduction*, *convection* and *radiation*.
**Conduction** can be reduced by the use of insulation.
**Convection** in the gap between the panes of double glazing can be reduced by filling it with a heavy gas such as argon.
**Radiation** of long wave infra-red radiation can be reduced by the use of **low emissivity (low-e) coatings**.

# *Availability of Solar Radiation*

- **Pyranometers** are devices that measure the energy received from solar radiation. They contain carefully calibrated thermoelectric elements fitted under a glass. A voltage proportional to the total incident light energy is produced and then recorded electronically.

- Near the equator, annual solar radiation is 2000-2500 kWh $m^{-2}$ $y^{-1}$. The average per day in July is 7-8 kWh $m^{-2}$. (1.5-2 in winter).

- In northern climates, this can be ~ 1000 kWh $m^{-2}$ $y^{-1}$ . The average per day in July is 4-5 kWh $m^{-2}$ . (0.5 in winter).

# Tilt and Orientation

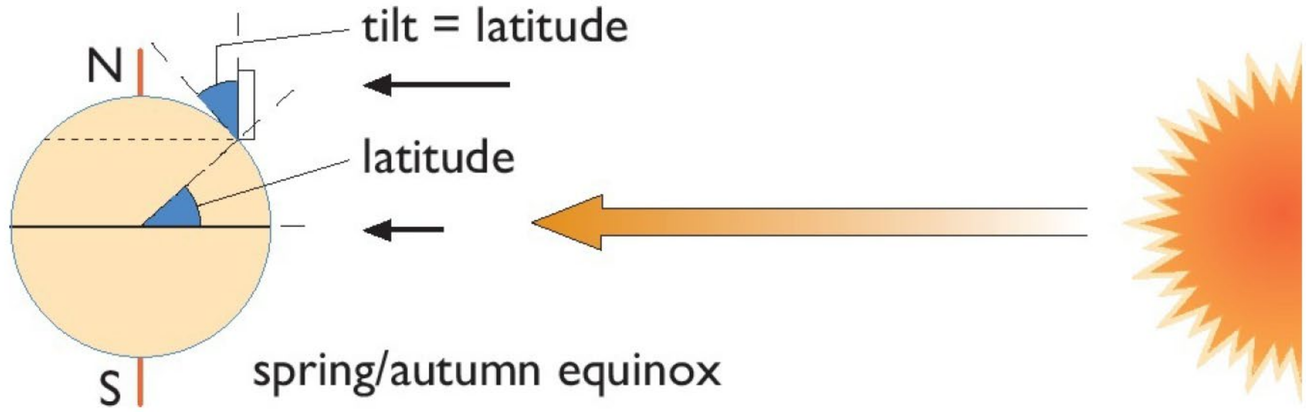
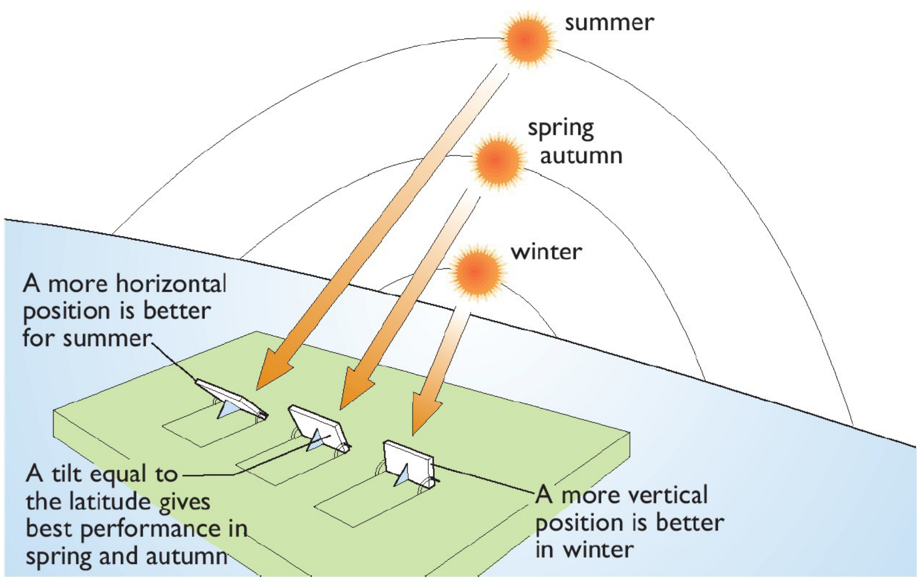



**Figure 3.9** A surface tilted at the latitude angle will be perpendicular to the Sun's rays at mid-day on the spring or autumn equinox

# Tilt and Orientation



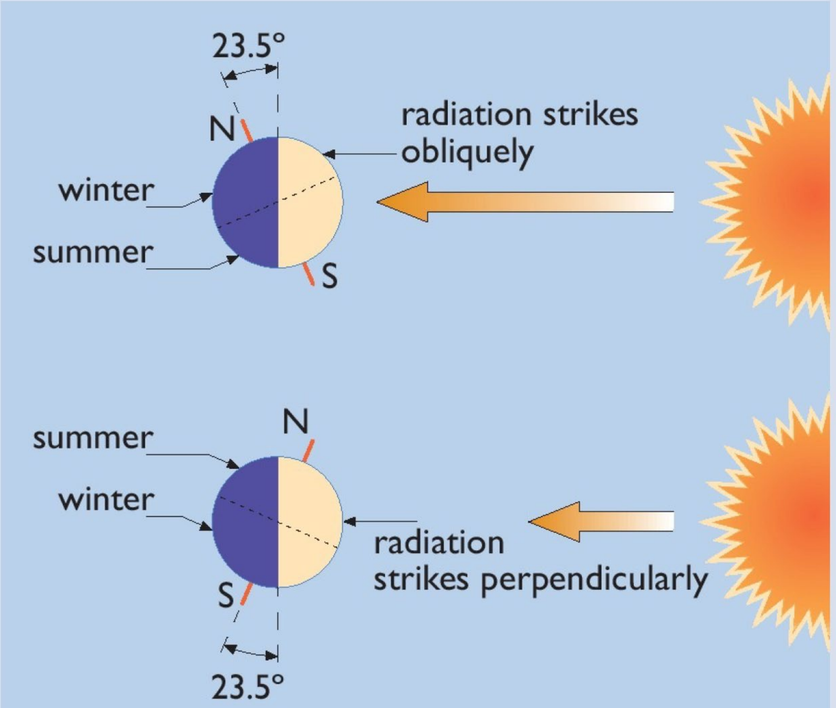




**Table 3.1** Effect of tilting a south-facing collection surface (data for Kew, near London, latitude 52° N)

| Tilt /° | Annual total radiation /kWh $m^{-2}$ | June total radiation /kWh $m^{-2}$ | December total radiation /kWh $m^{-2}$ |
|---|---|---|---|
| 0 – Horizontal | 944 | 153 | 16 |
| 30 | 1068 | 153 | 25 |
| 45 | 1053 | 143 | 29 |
| 60 | 990 | 126 | 30 |
| 90 – Vertical | 745 | 82 | 29 |

# *Glass Properties*

# Spectral Transmission of Glass

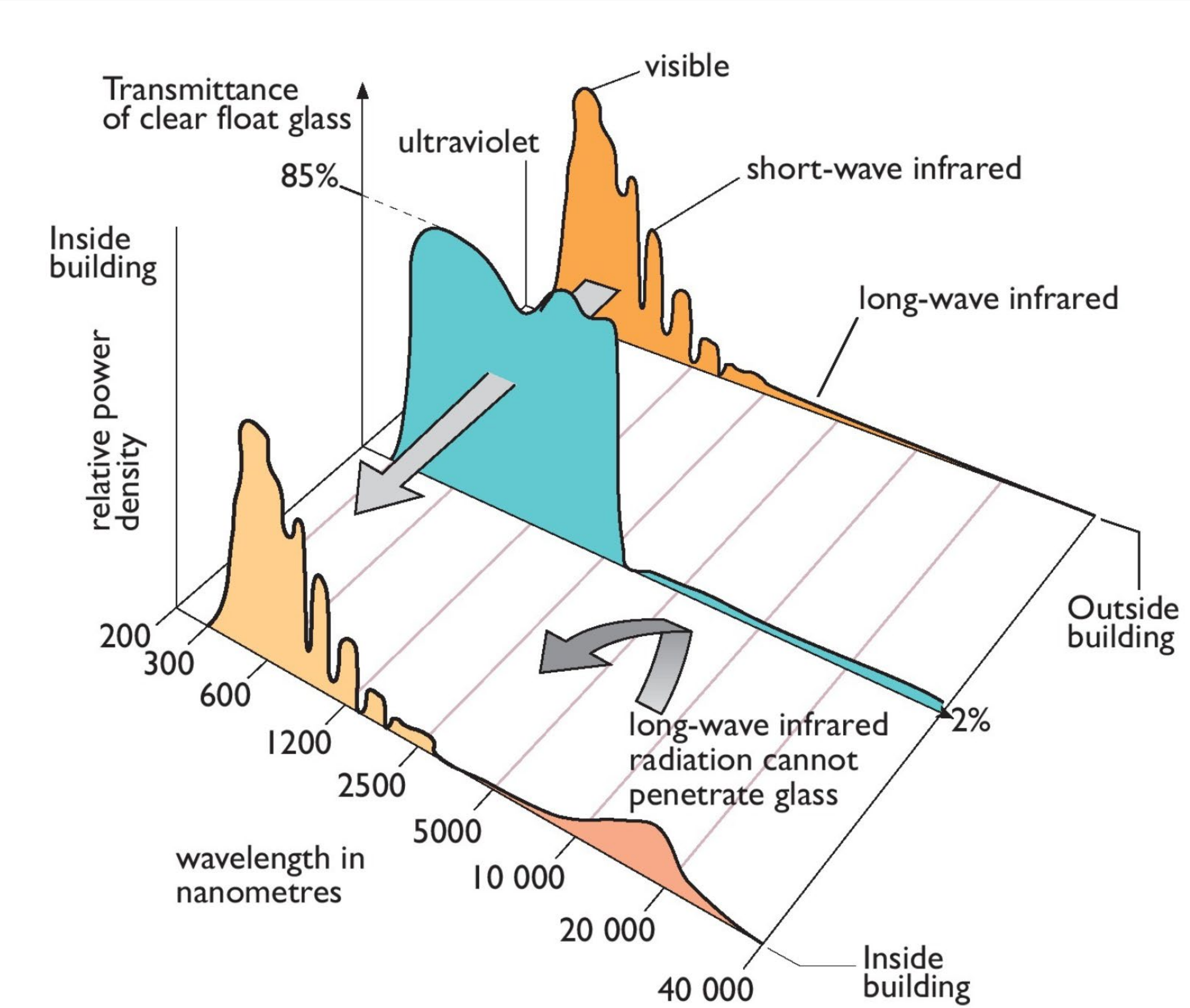



**Figure 3.13** Spectral transmittance of glass

# Optical Properties of Glazing

Manufacturers maximize **transmittance** (the fraction of incident light that passes through it) by minimizing the iron content of the glass.

Table 3.2 shows the optical properties of commonly used glazing materials. They high solar transmittance (close to 1.0), but the long-wave infrared transmittance is very low.

**Table 3.2** Optical properties of commonly used glazing materials

| Material | Thickness /mm | Solar transmittance | Long-wave infrared transmittance |
|---|---|---|---|
| Float glass (normal window glass) | 3.9 | 0.83 | 0.02 |
| Low-iron glass | 3.2 | 0.90 | 0.02 |
| Perspex | 3.1 | 0.82 | 0.02 |
| Polyvinyl fluoride (tedlar) | 0.1 | 0.92 | 0.22 |
| Polyester (mylar) | 0.1 | 0.87 | 0.18 |

# *Glass Properties*

- **Glass and other plastic glazing materials**, have the ability to transmit light but block the re-radiation of long-wave infrared radiation (heat).

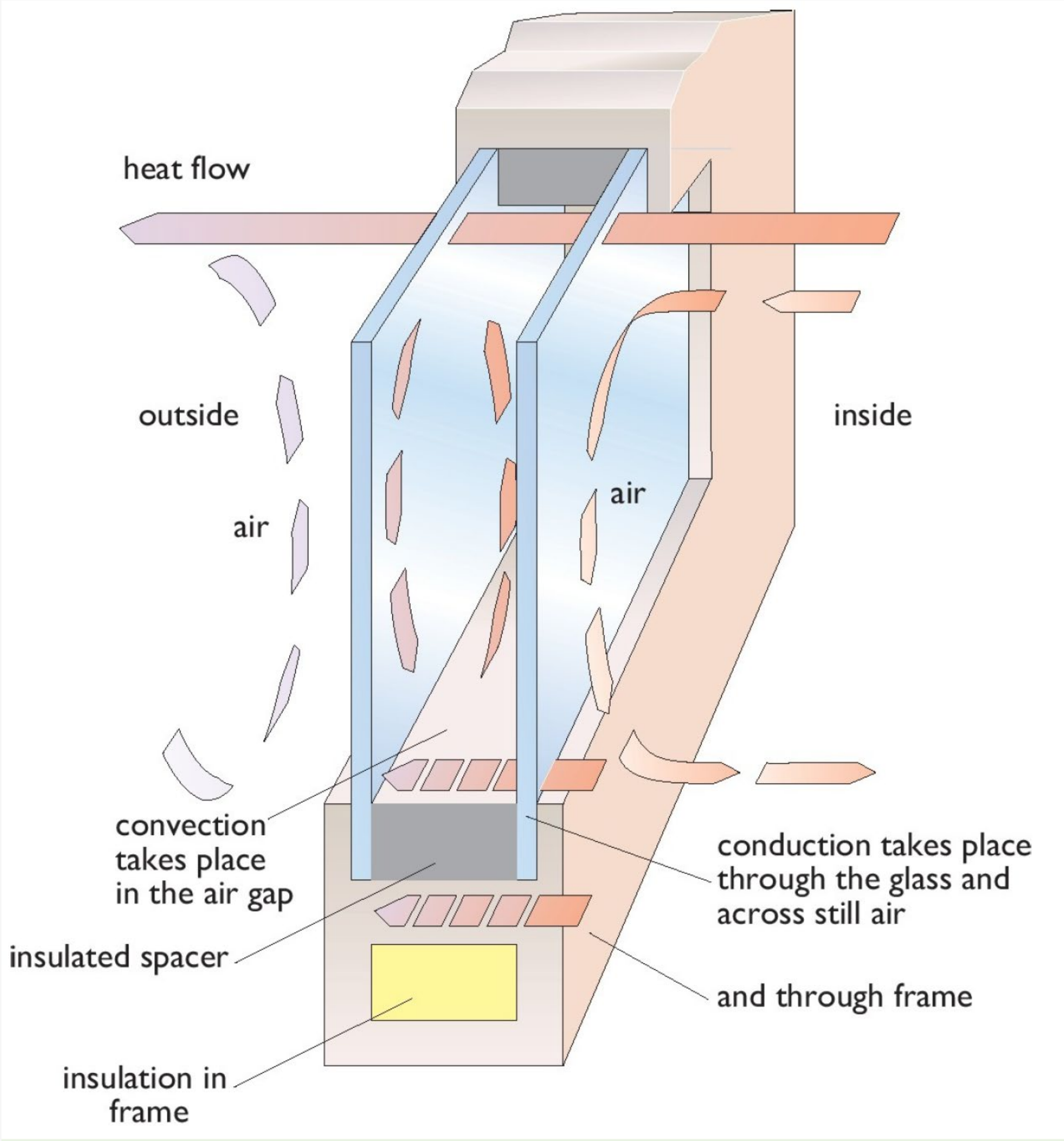
- There are three basic mechanisms of heat loss through a double glazed window: *conduction*, *convection* and *radiation*.

- **Conduction** can be reduced by the use of insulation.

- **Convection** in the gap between the panes of double glazing can be reduced by filling it with a heavy gas such as argon.

- **Radiation** of long wave infra-red radiation can be reduced by the use of **low emissivity (low-e) coatings**.

# Heat Flow in Double Glass



# *Window U-Value*

- heat flow rate per square meter = $U$-value × temperature difference.

- The lower the $U$-value, the better the insulation performance.

**Table 3.3** Indicative $U$-values for windows with wood or PVC-U frames

| **Glazing type** | **W m$^{-2}$ K$^{-1}$** |
|---|---|
| Single glazing | 4.8 |
| Double glazing (normal glass, air filled) | 2.7 |
| Double glazing (hard coat low-e, emissivity = 0.15, air filled) | 2.0 |
| Double glazing (hard coat low-e, emissivity = 0.2, argon filled) | 2.0 |
| Double glazing (soft coat low-e, emissivity = 0.05, argon filled) | 1.7 |
| Triple glazing (soft coat low-e, emissivity = 0.05, argon filled) | 1.3 |

# *Example on Heat Loss*

What is the rate of heat loss through a large single-glazed window with an area of 2 $m^2$, on a day when the outdoor and indoor temperatures are 5 °C and 20 °C respectively?

Table 2.3 shows that the *U*-value for this window is 4.8 W $m^{-2}$ $K^{-1}$, so the loss rate is
2 × 4.8 × (20 – 5) = 144 W
Note that, if the temperature difference remained the same throughout 24 hours, the total loss would be almost
3.5 kWh. If this window was replaced with the best of the glazing types shown in Table 3.3, this loss would be reduced to under 1 kWh. Although windows are an important route by which solar energy can be collected, their role in cutting unnecessary heat losses is just as important.

# *Low-Temperature Solar Energy Applications*

# *Low-Temperature Applications*

## Domestic water heating

Incoming mains water is usually at a temperature close to that of the ground at about 1 meter depth, approximately 12 °C in the UK, varying only slightly over the year, and it has to be heated up to 60 °C

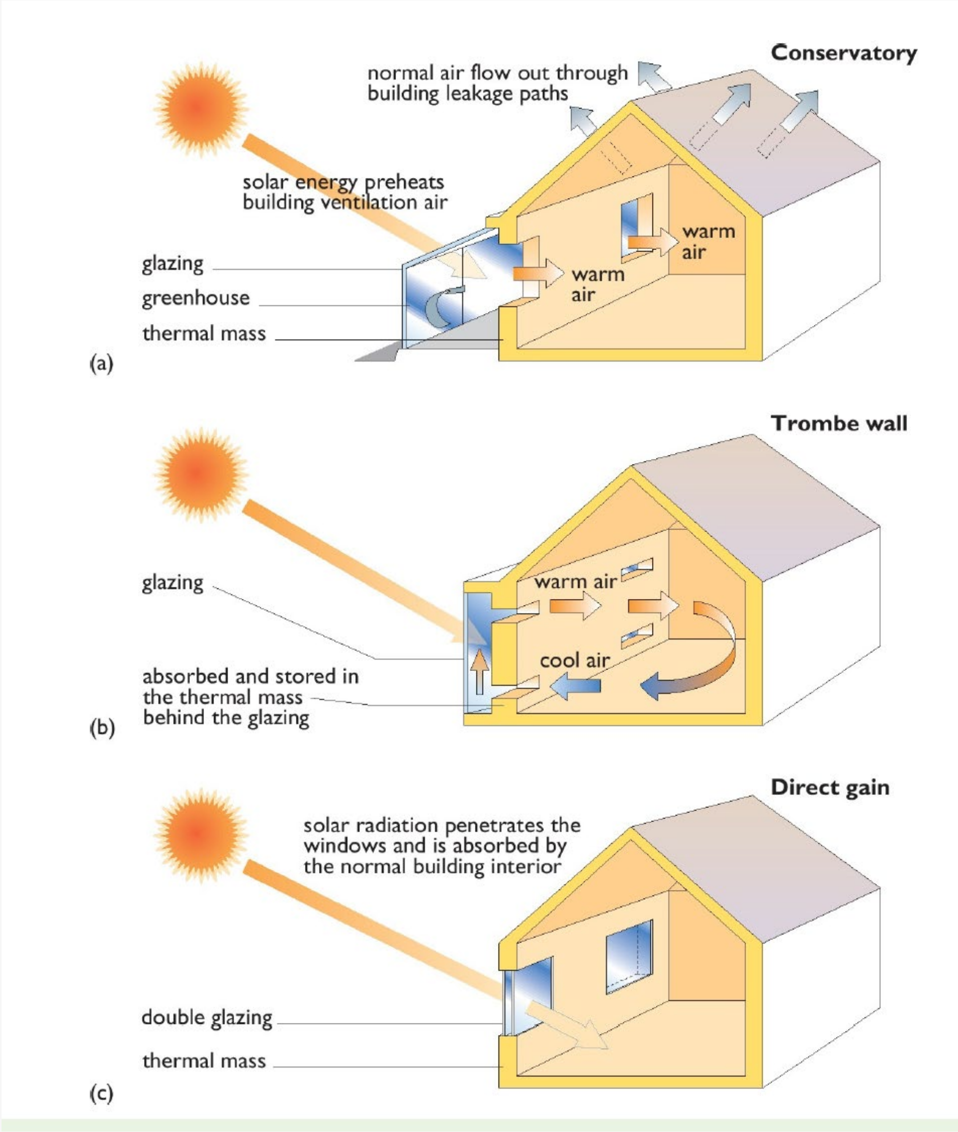
## Domestic space heating

Space heating involves warming the interior spaces of buildings to internal temperatures of approximately 20 °C.

The suitability of solar energy for space heating is dependent on the local climate, often in places that are both cold and sunny in winter.

# Varieties of Solar Heating Systems

*(a)Conservatory*
*(b)Trombe Wall*
*(c)Direct Gain*
*(d)Swimming Pool Heating*



# *Active Solar Heating*

# Solar Collectors for Low-Temperature

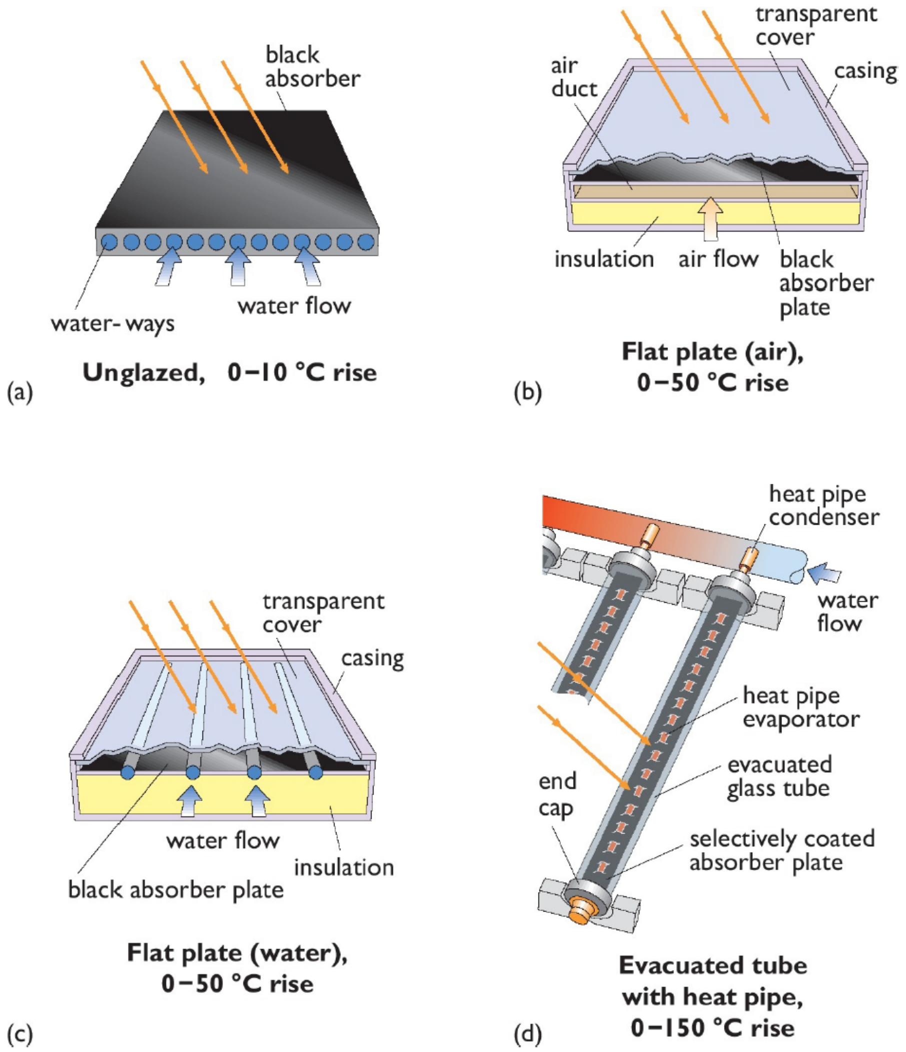



**Figure 3.20** Solar collectors for low-temperature collection

# *Passive Solar Heating*

# Direct gain buildings as solar collectors

(1) a large area of south-facing glazing to capture the sunlight
(2) thermally heavyweight construction (dense concrete or brickwork). This stores the thermal energy through the day and into the night
(3) thick insulation on the outside of the structure to retain the heat.

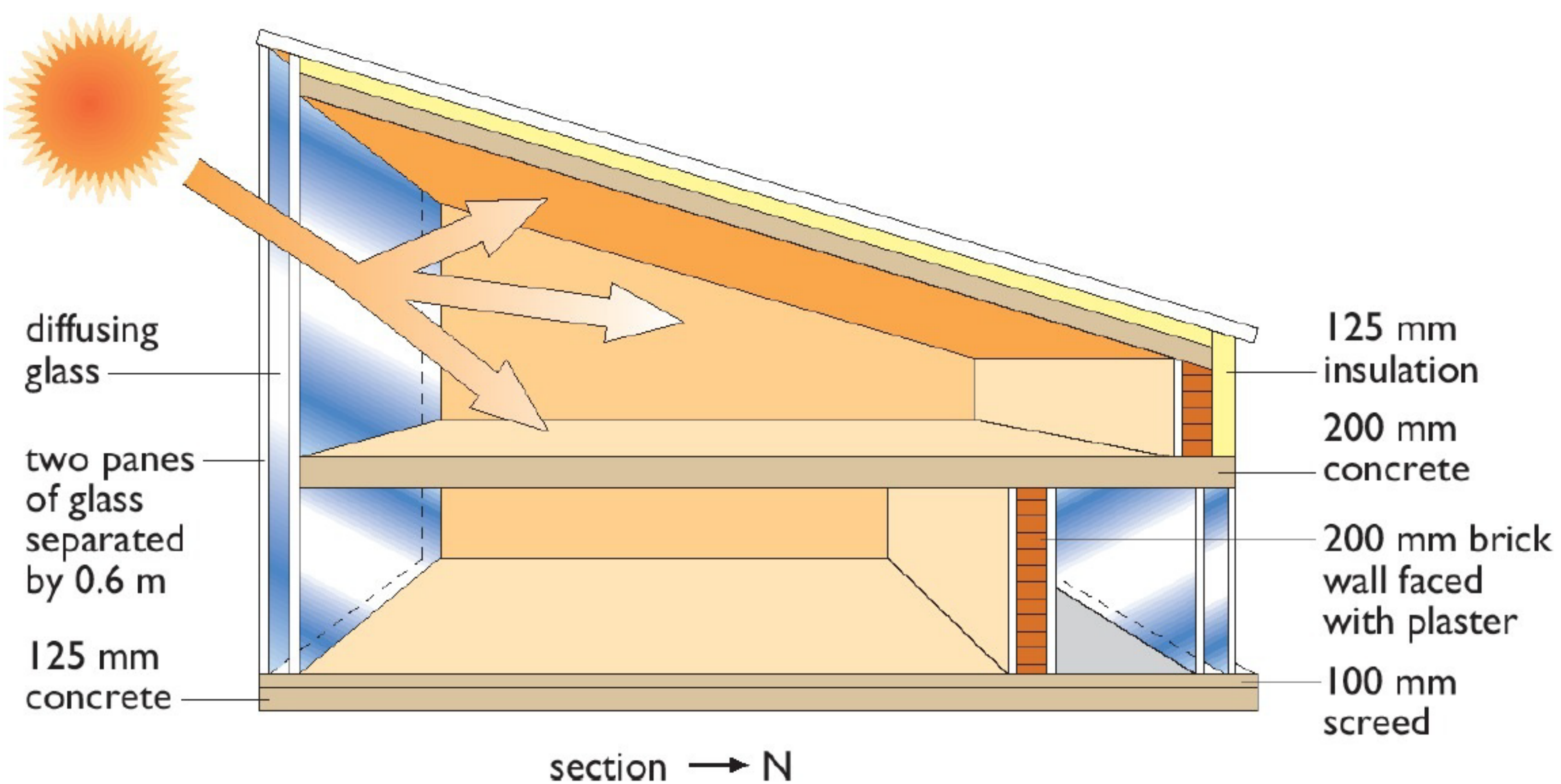



**Figure 3.23** Solar Campus – section

# *Window Energy Balance Depends on:*

(1) the building's average internal temperature
(2) the average external temperature
(3) the available solar radiation
(4) the transmittance characteristics of the window, its orientation and shading
(5) the *U*-value of the window, which is, in turn, dependent on whether it is single or double glazed (or even better insulated).

# Windows as Passive Solar Systems

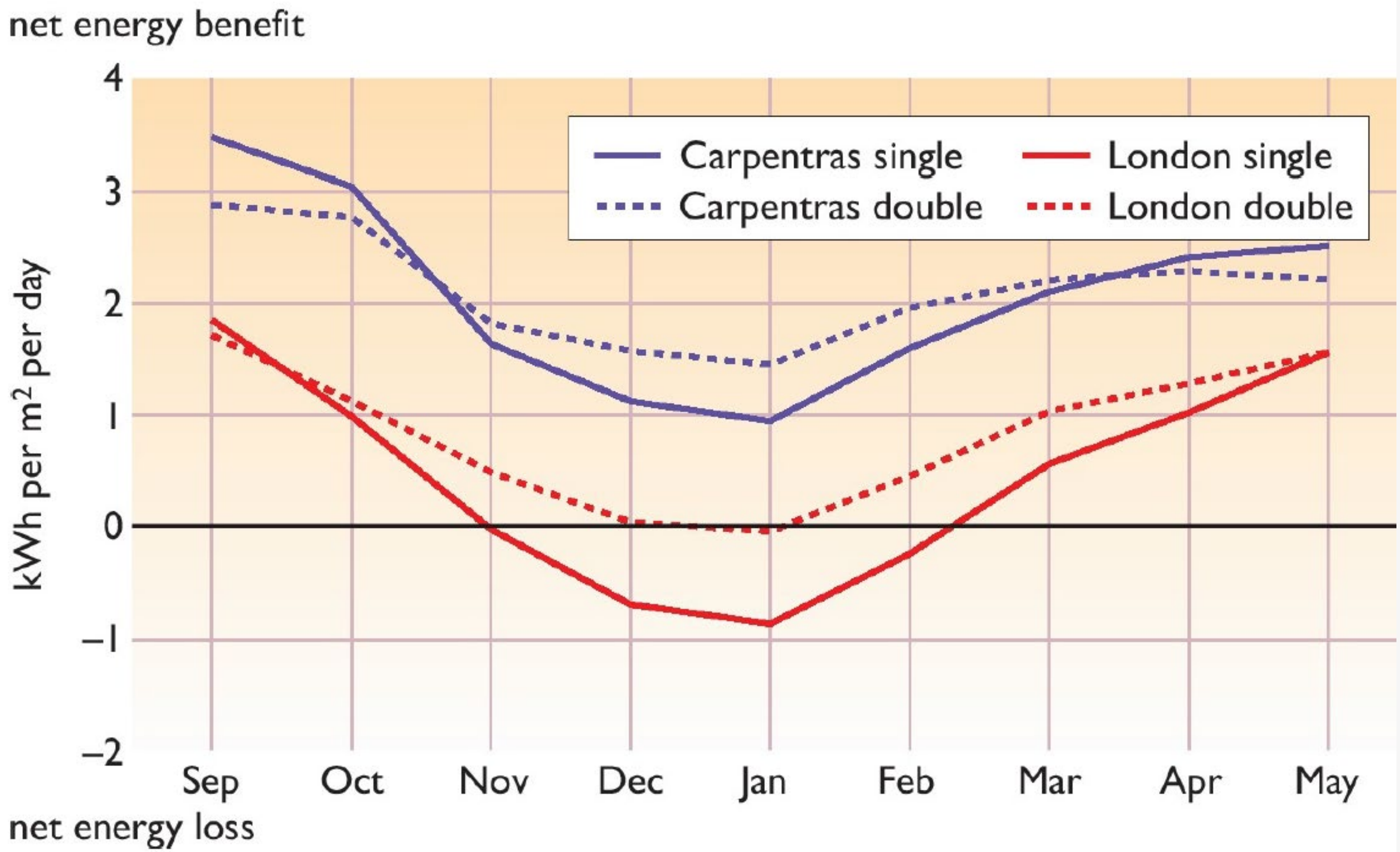



**Figure 3.25** Window energy balance: London and Carpentras, in the south of France

# Passivhaus Design

- The house is 'passive' in the sense that it does not need a conventional large heating system.

- This form of design has been used in over 30 000 buildings across the world to date.

- In Ludwigshafen in south-west Germany the passive house includes:

  - At least 200 mm thickness of foam insulation on the roof and in the walls
  - Triple-glazed windows with argon filling and low-emissivity coatings on the glass to cut the heat loss
  - Mechanical ventilation with heat recovery (MVHR); this uses heat recovered from outgoing air to preheat incoming fresh air
  - A fuel cell based combined heat and power (CHP) unit.

# General passive solar heating techniques

(1) They should be well-insulated to keep down the overall heat losses.
(2) They should have a responsive, efficient heating system.
(3) They should face south. The glazing should be concentrated on the south side, as should the main living rooms, with little-used rooms, such as bathrooms, on the north.
(4) They should avoid over-shading by other buildings in order to benefit from the essential mid-winter sun.
(5) They should be ‘thermally massive’ to avoid overheating in summer.

# Design Steps in Low-Energy Housing

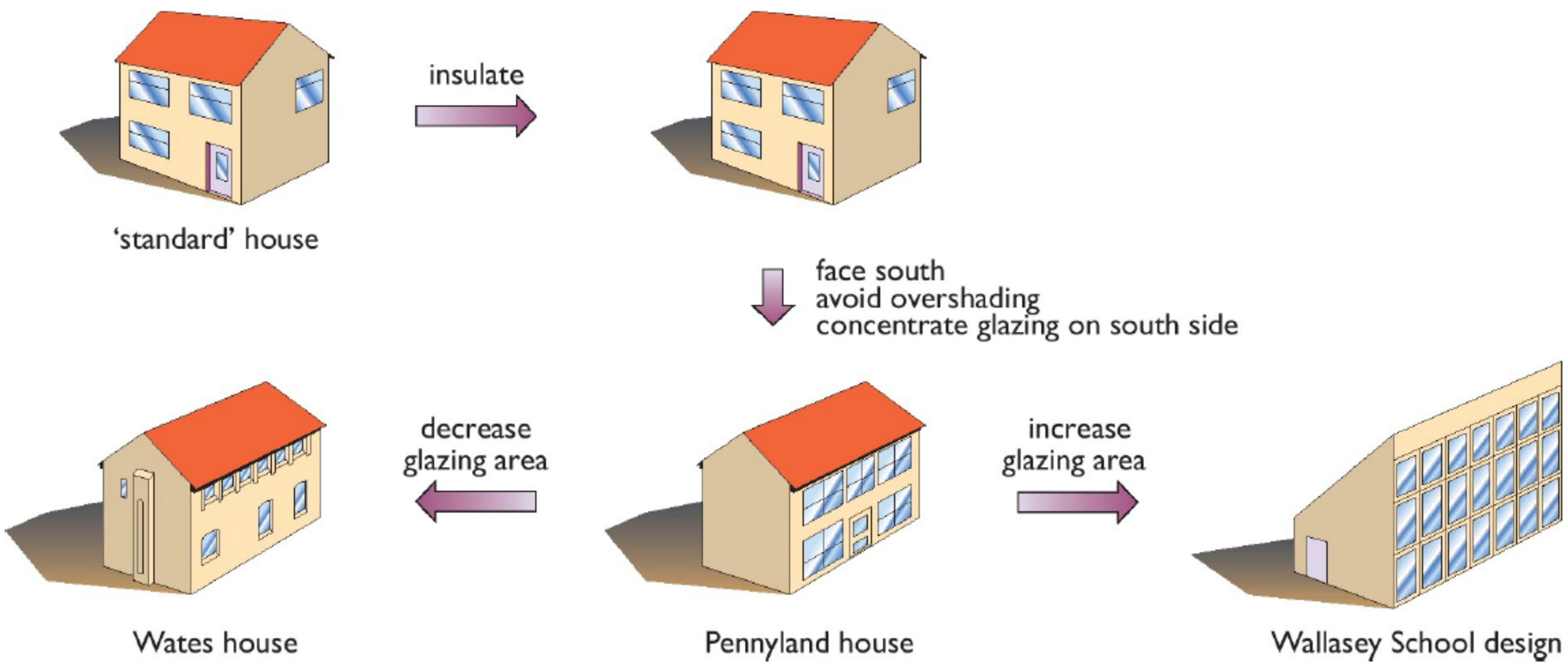



**Figure 3.30** Design steps in low-energy housing

## *Daylighting*

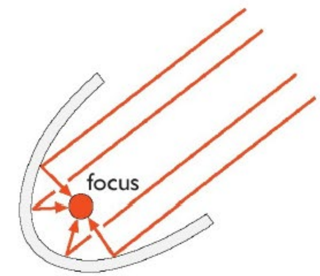
# *Daylighting makes the most of natural daylight*

- Traditional techniques include:
- shallow-plan design, allowing daylight to penetrate all rooms and corridors
- light wells in the center of buildings
- roof lights
- tall windows, which allow light to penetrate deep inside rooms
- the use of task lighting directly over the workplace, rather than lighting the whole
- building interior.

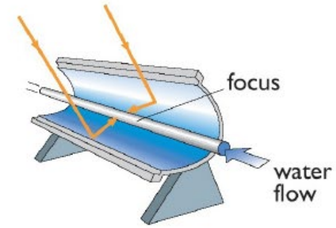
# *Solar Thermal Engines*

# Concentrating Solar Power (CSP)

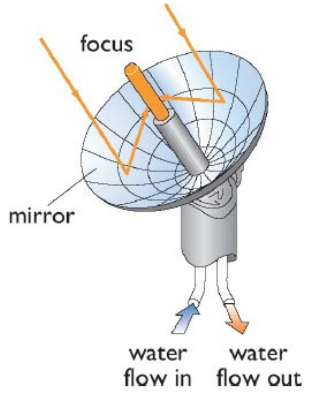
- The most common method of concentrating solar energy is to use a parabolic mirror.
- In the *line focus or trough collector* the Sun's rays are focused onto a pipe running down the center of a trough.
- The pipe is likely to carry a high temperature heat transfer fluid such as a mineral oil.
- Such systems are mainly used for generating steam for electricity generation.
- A line focus collector can be oriented with its axis in either a horizontal or a vertical plane.
- In the *point focus or dish collector* the Sun's image is concentrated on a steam boiler or a Stirling engine in the center of the mirror.
- The *fresnel* collector is a variant of the line focus collector in which a series of long strips of flat mirror.




(a) Parabolic mirror brings light to a precise focus in centre




(b) **Line focus, 200 –400 °C**



# Example on Carnot Engine Efficiency

$$\text{maximum efficiency} = 1 - \frac{T_{\text{out}}}{T_{\text{in}}}$$

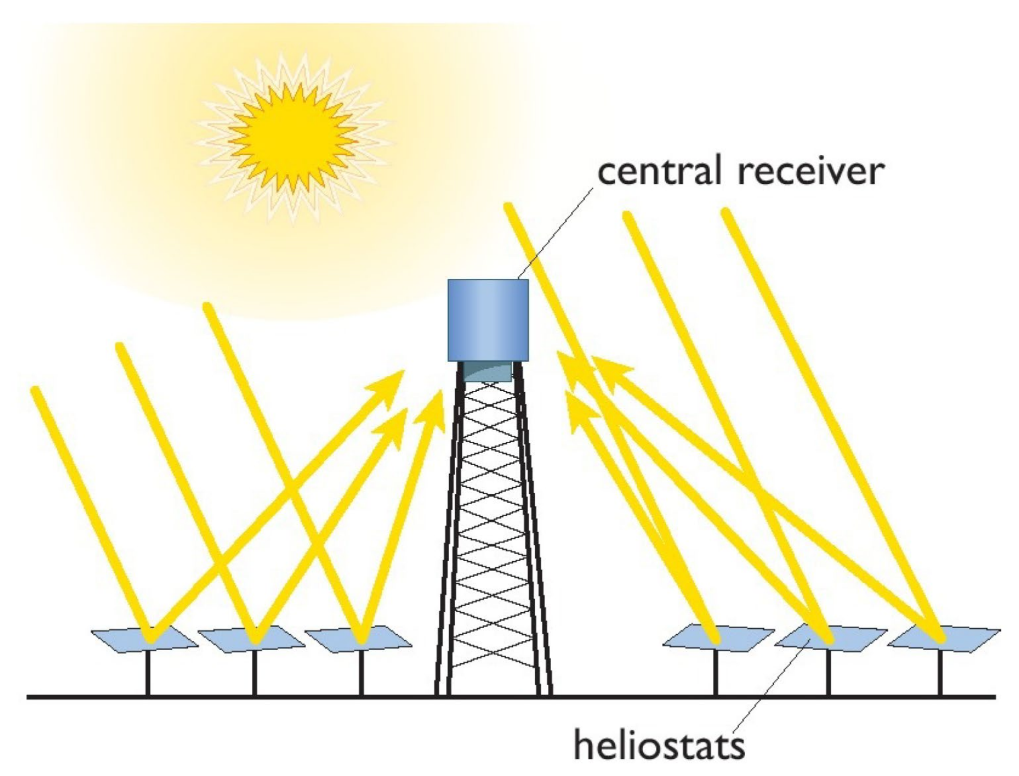
In a modern CSP plant well-designed parabolic trough collectors might produce steam at 350 °C.
This would be fed to a steam turbine and low-temperature heat would be rejected in cooling towers at 30 °C.

The theoretical efficiency of the system would therefore be:
1 – (30 + 273)/(350 + 273) = 0.51 or 51%.

Its practical efficiency is more likely to be about 25%, due to various losses.
Normally, to boil water, its temperature must be raised to at least 100 °C.
Organic
Rankine Cycle (ORC) systems have been developed that use refrigerants with lower boiling points. These can be used with low-temperature solar engines, for example in Ocean Thermal Energy Conversion (OTEC) systems.

# *Solar Power Towers*

These use a large array of heliostats (steerable mirrors) on the ground which focus the Sun's rays onto a central receiver at the top of a tower.




A 10 megawatt (MW) plant, *Solar One*, was built at Barstow in California in 1981. Solar Two included thermal energy storage (or TES) allowing it to produce electricity on a 24-hour basis. This involves storing a molten salt mixture of sodium nitrate and potassium nitrate with a melting point of over 200 °C and heating it to 500$^0$C. This is used to produce steam later in the day

# Large Solar-Thermal Systems

**Figure 3.42** The PS 10 (completed 2007) and PS20 (completed 2009) power tower plants near Seville in Spain have been followed by many similar projects.

# 10 & 20 MW Systems in Spain

# *Large Solar-Thermal Systems*

The 377 MW Ivanpah plant in California, opened in 2014, has three power towers and covers an area of 14 $km^2$.

# *Parabolic trough concentrating collector systems*

**Figure 3.43** SEGS solar collector field at Kramer Junction in southern California

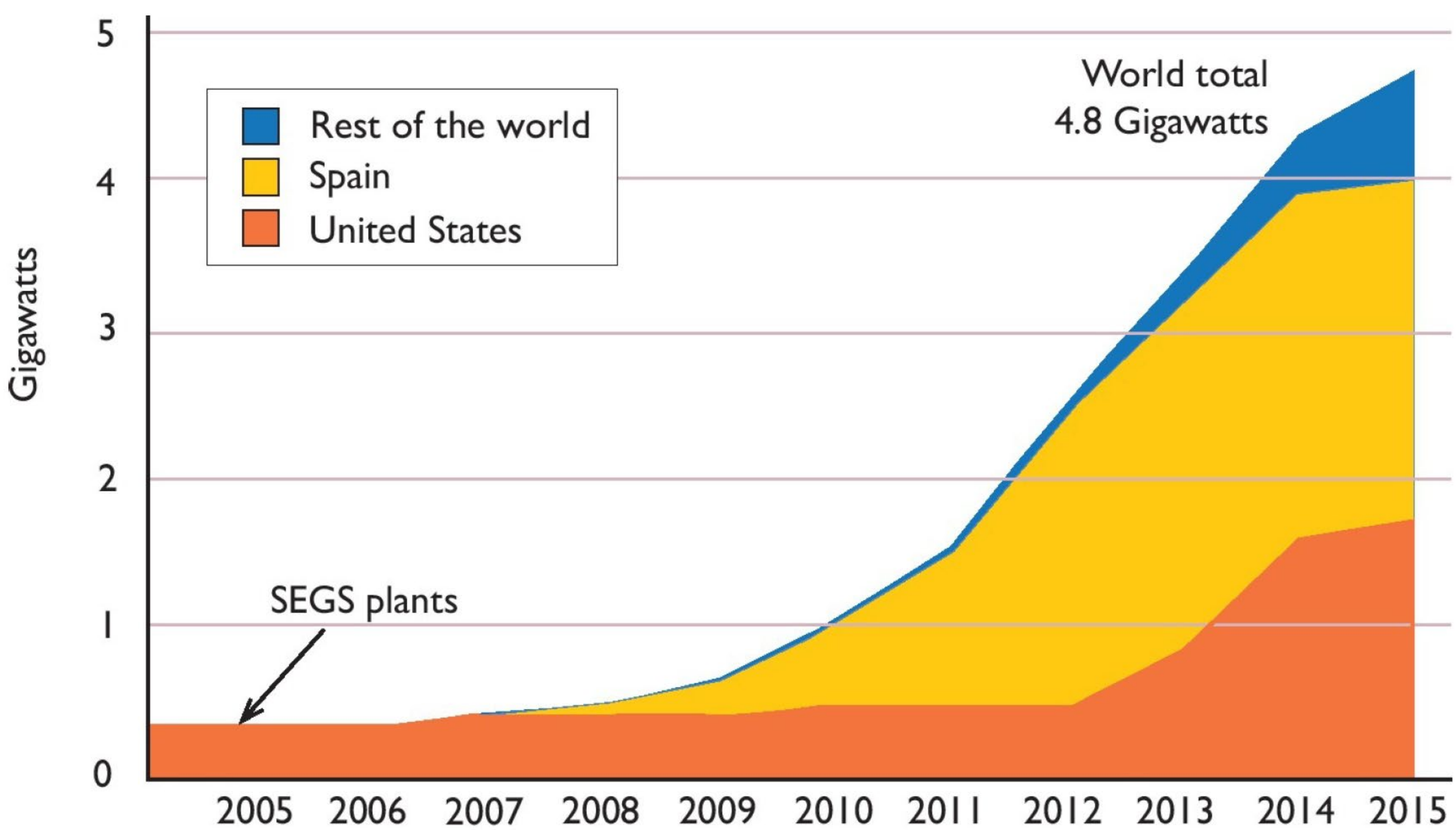
The collectors heat synthetic oil to 390 °C, which can then produce high-temperature steam via a heat exchanger. The five plants at Kramer Junction (SEGS III to VII) have recorded annual plant efficiencies of 14% and peak efficiencies of up to 21.5%

# Parabolic Dish Concentrator Systems

A pilot scheme of 60 dishes each driving a 25 kW Stirling engine was constructed inImperial Valley in Arizona in 2010

**Figure 3.45** An array of 60 parabolic dishes each with a 25 kW Stirling engine constructed at Maricopa in Arizona in 2010

# World Growth in Concentrating Solar Power



# CSP VERSUS PV Systems

**Table 3.5** Comparison of Concentrating Solar Power and Photovoltaics

| **Utility scale concentrating solar power** | **Photovoltaics** |
|---|---|
| **Advantages** | **Advantages** |
| ‘low tech’ use of conventional steam turbine technology and conventional glass production for mirrors | basic simple systems have no moving parts and very low maintenance costs |
| can use natural gas as a ‘top-up’ and to generate in the evening | can operate under clear and cloudy skies |
| proven performance for over 25 years for parabolic trough systems | rapidly falling prices have encouraged investors |
| | can be deployed in small project sizes as finance allows |
| compatible with molten salt energy storage with potential to produce electricity day or night. | proven performance at a small scale. |
| **Disadvantages** | **Disadvantages** |
| requires clear skies | ‘high-tech’ PV panels have to be made in specialist factories |
| utility scale projects require large up-front capital investments. | |
| | any energy storage has to be electrical. |

# Low-Temperature Solar Systems

## Solar ponds

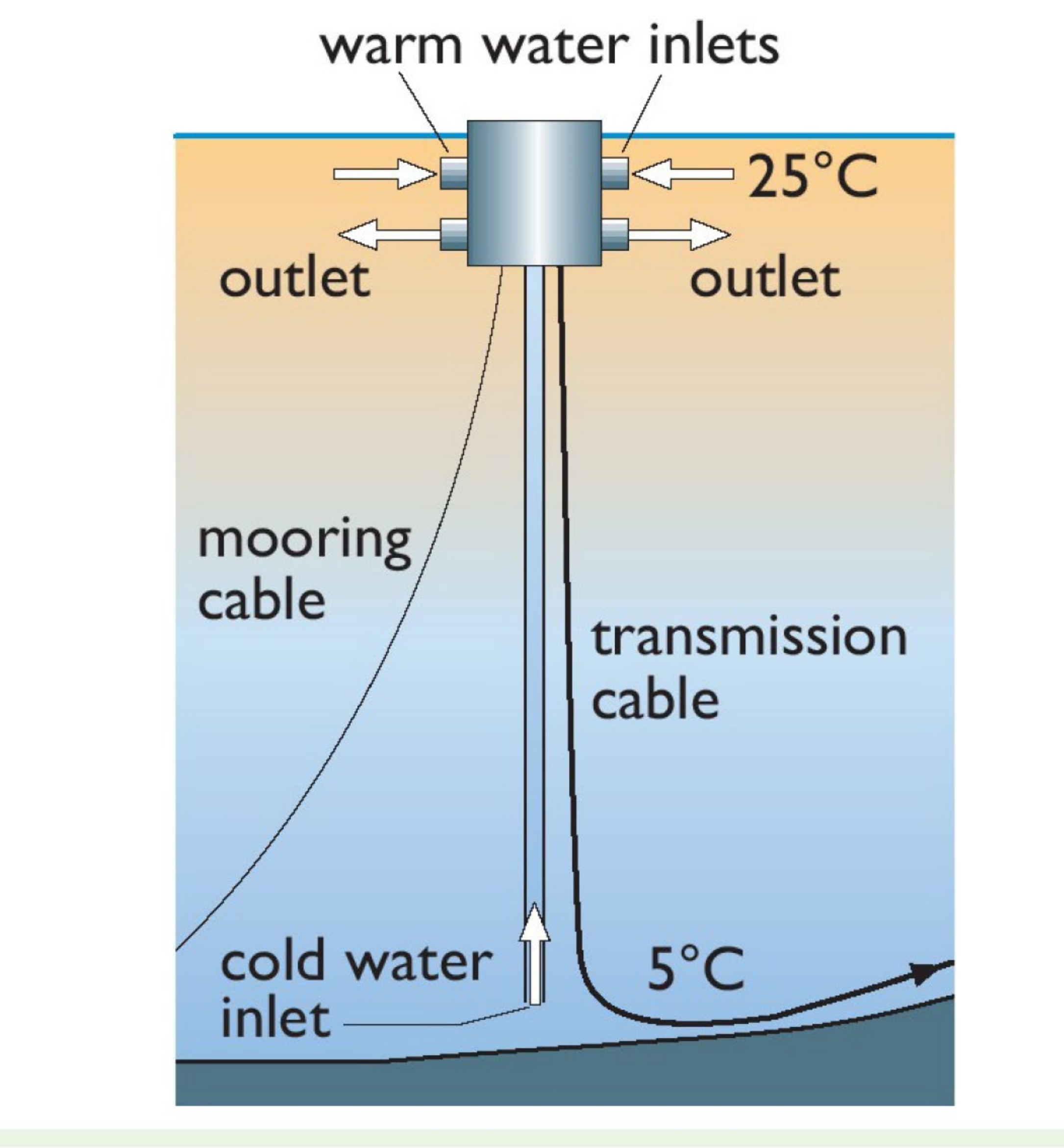
- Solar ponds use a large, salty lake as a kind of flat plate collector.
- If the lake has the right gradient of salt concentration (salty water at the bottom and fresh water at the top) and the water is clear enough, solar energy is absorbed at the bottom of the pond.
- The temperature at the bottom of the pond can reach 90 °C. This is a high enough temperature to run an Organic Rankine cycle (ORC) engine.

## Ocean thermal energy conversion (OTEC)

- Ocean thermal energy conversion essentially uses the sea as a solar collector.
- It exploits the small temperature difference between the warm surface of the sea and the cold water at the bottom.
- In deep tropical waters, 1000 m deep or more, this can amount to 20 °C.
- This is sufficient to drive an ORC engine, using ammonia or an ammonia/water mixture as the working fluid.

# OTEC ORC systems

The engineering difficulties are enormous. An OTEC plant producing 10 MW of electricity would need to pump nearly 500 cubic meters per second of both warm and cold water through its heat exchangers, whilst remaining moored in sea 1000 meters deep. Typically the pumps consume 20–30% of the electricity generated



# Solar-Thermal Process Steam

solar thermal enhanced oil recovery. High pressure steam is injected deep underground into oil fields to melt and flush out high-viscosity oil.


**Figure 3.49** The pilot solar thermal enhanced oil recovery plant at Amal West in Oman. The steam-generating parabolic concentrating solar collectors are housed inside a protective greenhouse. The new project is estimated to save nearly 6 PJ of natural gas, enough to generate electricity for over 200 000 Oman residents.

## *Points of Discussion on Economics, Potential & Environmental Impact*

- Domestic active solar water heating
- Passive solar heating and daylighting
- Solar thermal engines and electricity generation