Chapter 2: Solar thermal Energy

2.1 Introduction

• The Sun is the ultimate source of most of our renewable energy supplies.

• There are many aspects of thermal energy systems:

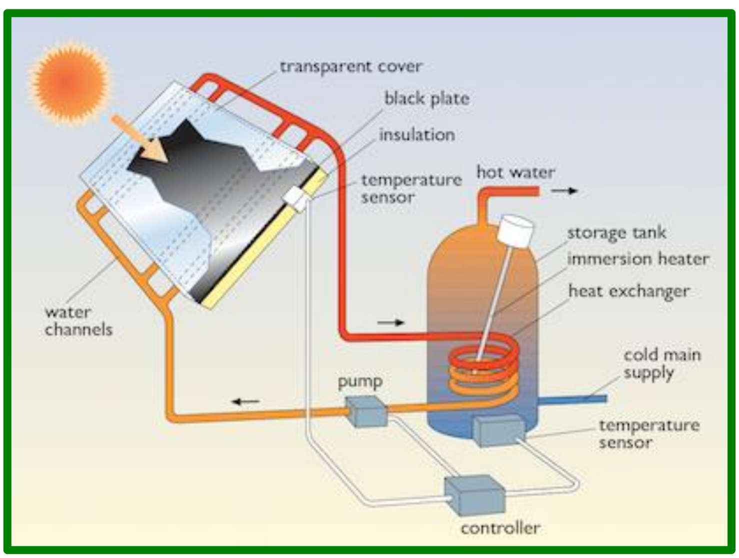
- active solar heating: like a discrete solar collector, on a house or a building (often includes an electric pump to circulate water)
- passive solar heating: direct absorption of solar energy, space heating, low-energy building design
- daylighting: making best use of natural daylight
- solar thermal engines: temperatures high enough to produce electricity
- heat pumps: draw energy from the outside environment

2.2 The rooftop solar water heater

• Basically, rooftop solar water heaters involve flat plate collectors. Germany a leader in Europe. Very common in Japan.

The *pumped* solar water heater

• A collector panel, typically 3-5 square meters, tilted to face the Sun, and mounted on a roof. Normally three components:



1) The main absorber might be a steel plate bonded to copper or steel tubing, through which water circulates. The plate is sprayed with special black paint or coated with a selective surface to maximize solar absorption. Covered with a single sheet of glass or plastic; the whole assembly is insulated on the back to cut heat losses.

2) A storage tank, typically around 200 liters capacity. Usually contains an electric *immersion heater* for winter use. The tank is insulated all around The hot water from the panel circulates through a heat exchanger.

3) A pumped circulation system. A sensor determines when to circulate the water. In very cold climates antifreeze is added.

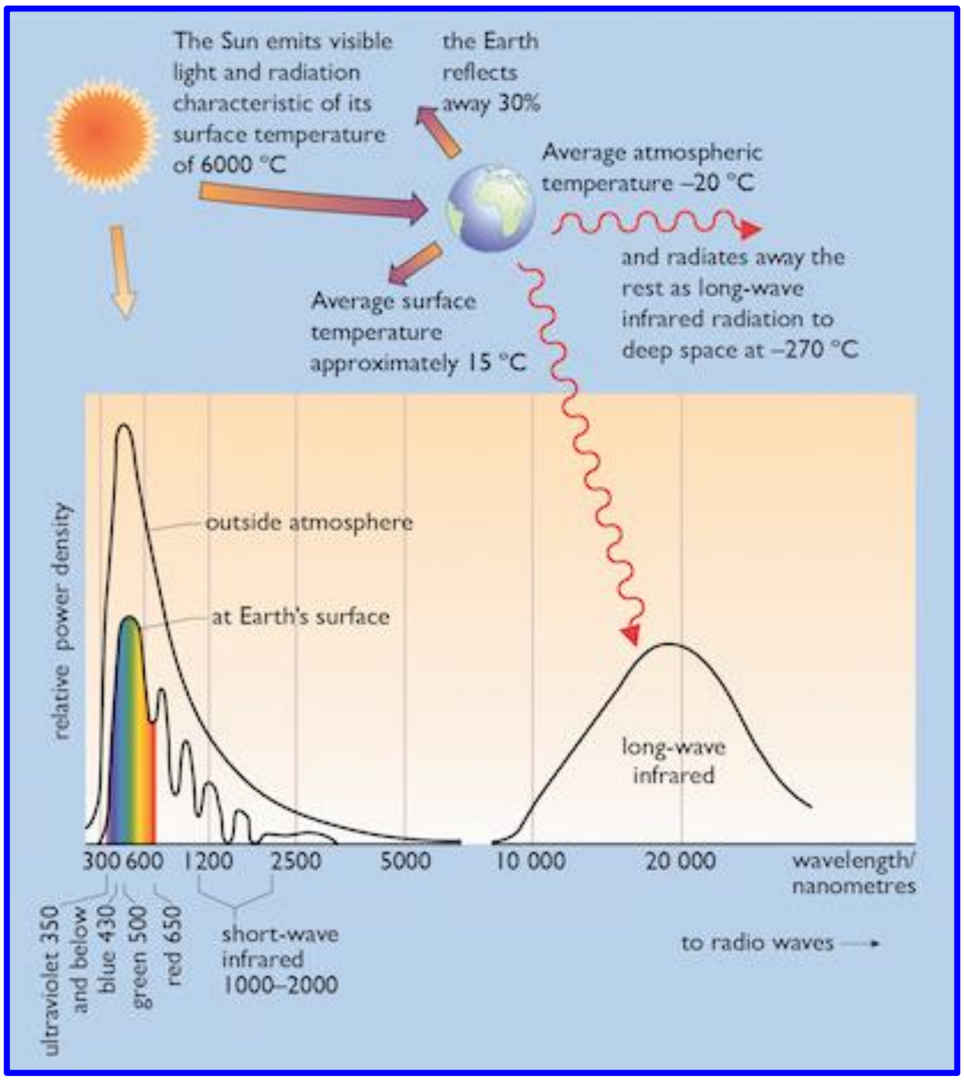
The (Mediterranean) thermosyphon solar water heater

• In climates where frost is no a concern, a simpler system can be made without a heat exchanger or pump. Heat naturally rises to the storage tank by **convection**. An electric immersion heater can be installed for use on cloudy days.

2.3 The nature and availability of solar radiation

The wavelengths of solar radiation

• Th Sun is an enormous nuclear fusion reactor, which converts hydrogen to helium at a rate of 4 million tons per second. It radiates energy by virtue of its high surface temperature, approximately 6,000 ^{0}C. The figure below shows where this energy goes:



• Earth has a ***average*** atmospheric temperature of -20 ^{0}C and a surface temperature of 15 ^{0}C.

It radiates energy at long-wavelength infrared to deep space, the temperature of which is only a few degrees above the absolute zero value: -273 ^{0}C.

Direct and diffuse radiation

- When solar radiation reaches Earth's atmosphere it is scattered (shorter wavelengths more than longer).

- This scattered light reaches he surface as diffuse radiation. That part that seems to come more directly from the Sun is called direct radiation.

- On a clear day the direct radiation can approach 1 kilowatt per square meter (1 kW m^{-2}), known as "1 sun" for solar collector testing purposes. In northern Europe about 50% of the radiation is diffuse and 50% direct.

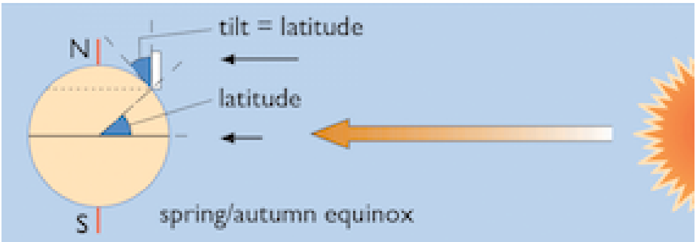
Availability of solar radiation

- Today, solar radiation at any location of Earth can be measured using a solarmeter. Energy is recorded as total energy incident on the horizontal surface. More fancy detectors can determine the direct and diffuse components.

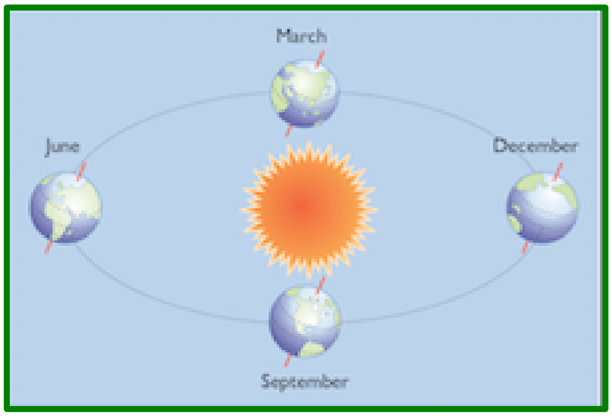
- Value highest near the equator: 2,000 kilowatt-hours per square meter per year (kWh $m^{-2}y^{-1}$), especially high desert areas. ONLY about 1,000 in northern Europe. South Europe = 1,500; high south-west US regions = 2,500.

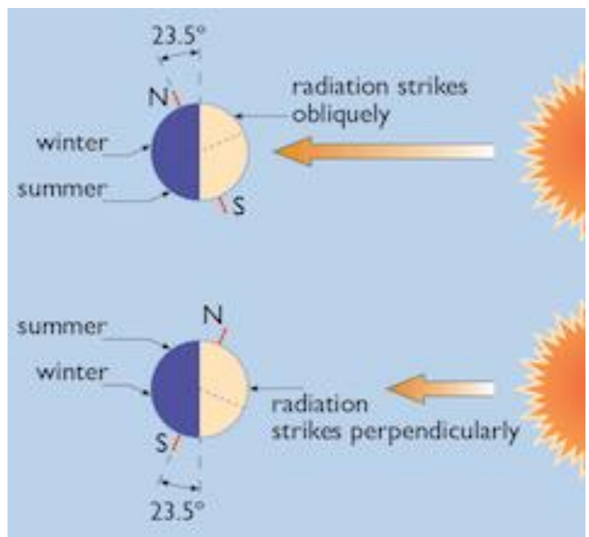
- Summer northern Europe gets about 5 kWh m^{-2} (per day); winter is only about 0.5 kWh m^{-2}. In the south it is between 6 and 7.5 kWh m^{-2}. Below map is for July.

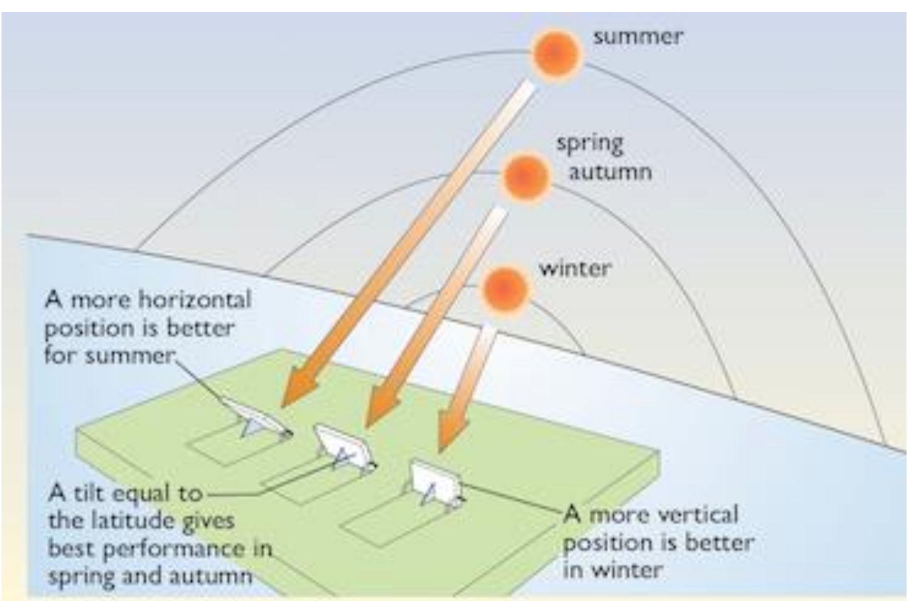
Tilt and orientation



• To collect as much radiation as possible, a surface should face south (if northern hemisphere) and must be tilted toward the Sun. The tilt depends on the latitude and at what time of the year used. If the tilt angle between the surface and the horizontal is equal to the latitude, it will be perpendicular to the Sun's rays at midday in March and September.







at about 21 June

at about 21 March September

at about 20 December

2.4 The magic of glass

• Most "low-temperature" solar collection depends on the properties of an amazing substance, glass. Glazed (= glass) windows were invented by the Romans, but an ability lost during the apply named "dark ages", and did not reappear until the 17th century.

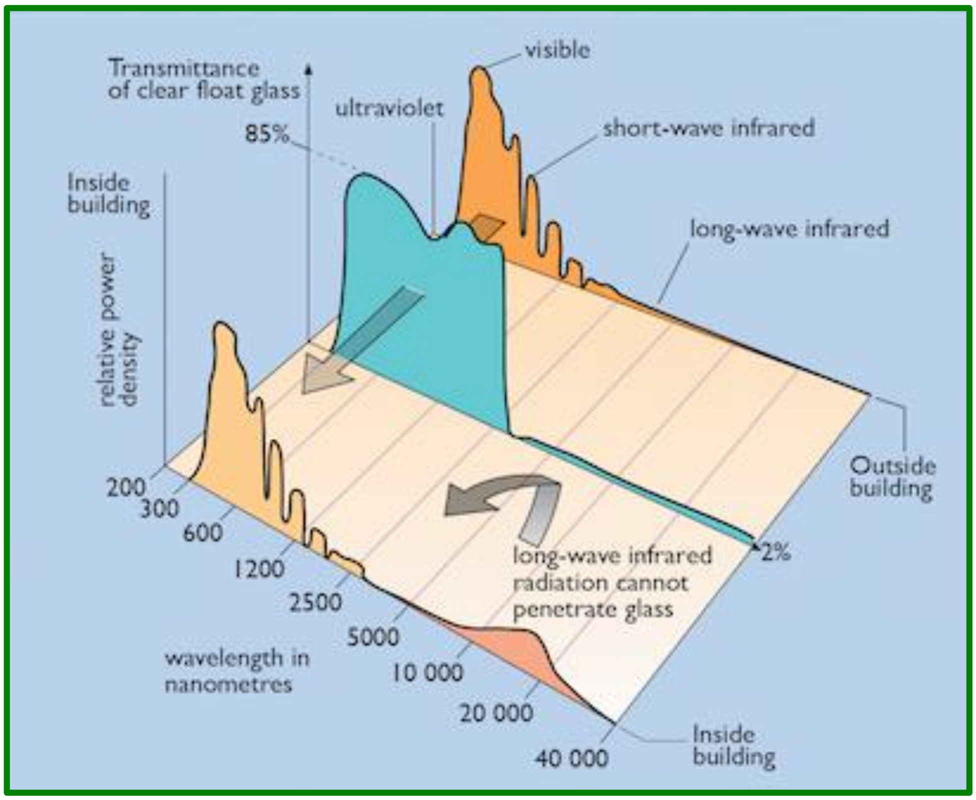
Transparency

• Glass is transparent to visible light and short-wavelength infrared radiation, but has the added advantage of being opaque to long-wavelength infrared re-radiated from a solar collector or building behind it

• TED talk:
"Why Is Glass Transparent?"
➔

• Amazing 'quartz' = SiO_2

• Solar cells made of Si



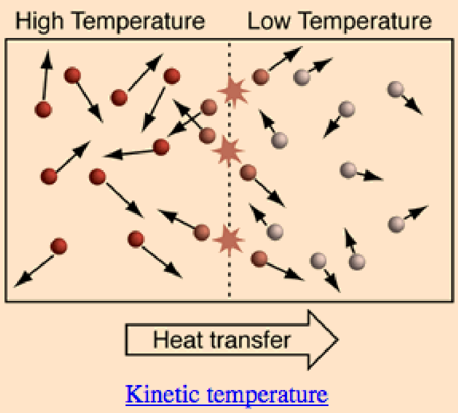
• Over the past few decades, enormous effort has been put to improving the performance of glazing (glass making), both to maximize its transparency to visible radiation, and to prevent heat escaping through it.

• The transmittance can be improved or maximized by minimizing the iron content.

Table 2.2 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

Temperature (the feeling of various degrees of "hotness" and "coldness") is actually in proportion to the average kinetic energy (speed) of atoms on the atmosphere or vibration of atoms or molecules in solids or liquids.



$$T_{kinetic} = \frac{2}{3k}\left[\overline{\frac{1}{2}mv^2}\right] = \frac{2}{3k}KE_{avg}$$

In the atmosphere the oxygen and nitrogen are – amazingly – traveling at about 1,700 km per hour!!!

• Heat-loss mechanisms

• Energy loss through windows is 4 & 5% of U.S. energy consumption. WOW!!! Causes annual loss of US$50 billion

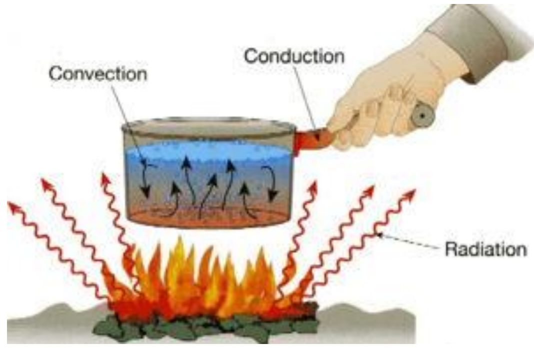
• Much research has tried to reduce this energy loss through windows and solar collector glazing. Heat energy ALWAYS from higher to lower temperature!. The rate depends on:

- temperature difference between the two sides
- total area available for the flow
- insulting qualities of the material

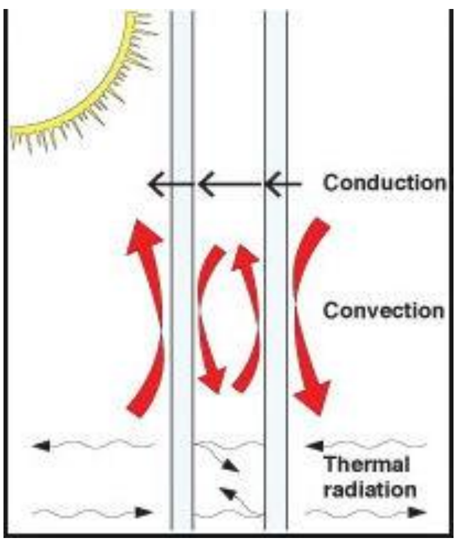
• There are three (3) mechanisms involved in the transmission of heat:

1) Conduction: Flow by contact, determined by the 'thermal conductivity' of the material and the temperature difference. METALS have high conductivities for both charge and heat.

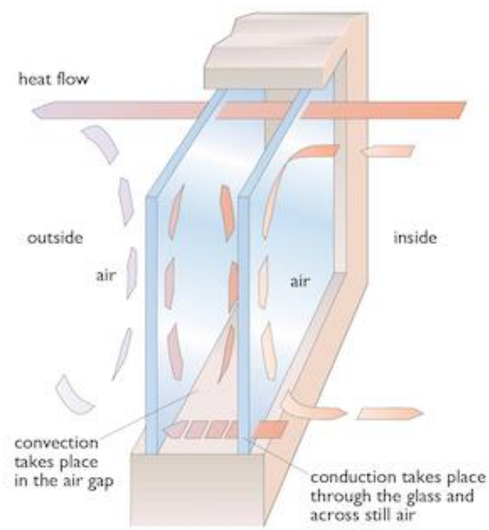
Insulators have low thermal conductivity. AIR is a good insulator. Most practical forms of insulation rely on small pockets of air, trapped for example between the panes of glazing, as bubbles in a plastic medium, or between fibers of mineral wool.



2) Convection: A warmed fluid, such as air, expands, becoming less dense and rising as a result. It occurs between the air and the glass on the inside and outside surfaces; in double glazing, it occurs in the air space between the panes. This can be reduced by filling double glazing by heavier, less mobile gas molecules, most commonly argon, though carbon dioxide and krypton are also used.



• How heat flows around a double-glazed window: The air space is normally about 16 mm wide. If it is too narrow, convection is difficult but conduction is easy because only a small thickness of air to conduct across. If too wide, convection currents can easily circulate. Also, there is infrared radiation across the air space which can be reduced by using low emissivity coatings.



• Transparent insulation developed involving transparent plastic containing bubbles of trapped insulating gas. But still technically problematic.

• Also the space between double gazing can be evacuated (vacuum), disallowing convection, but difficult to maintain.

• Can add transparent plastic film or triple or quadruple glazing.

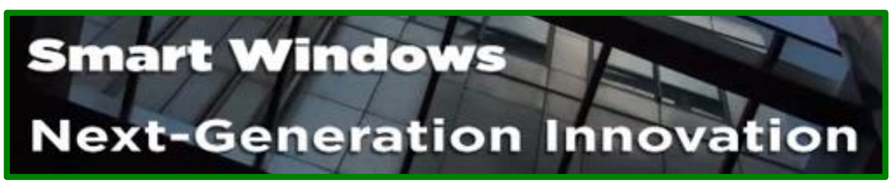
3) Radiation: Heat can also be radiated from high to low temperature, depending on the radiating material's emissivity. 'Low and high-E coatings' can be applied as needed.

Window U-factor: The actual performance of any particular building element is usually specified by a U-value, defined so that:

- heat flow rate per m^2 = U-value x temperature difference; lower BETTER

Table 2.3 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

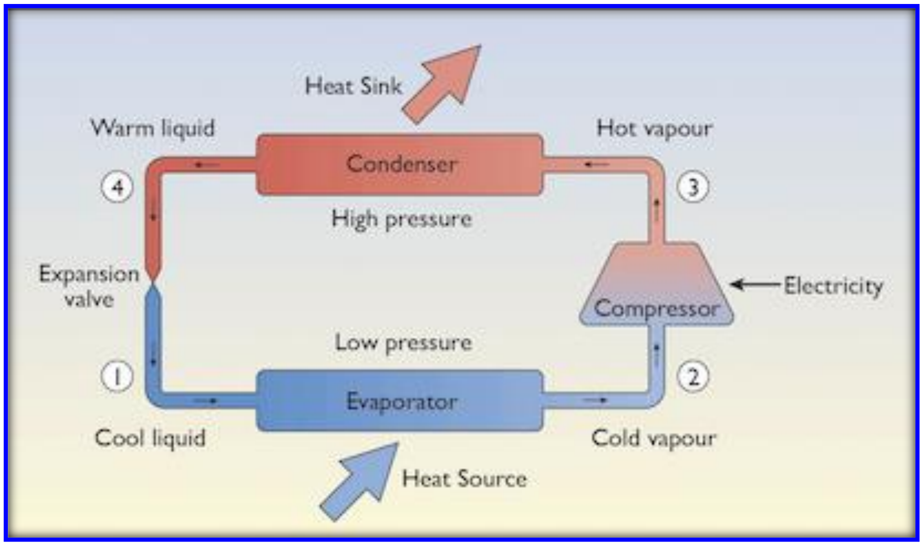


Clips 2, 3, 4

2.5 Low temperature solar energy applications

• Although *simple* solar systems are in principle ideal for supplying low-temperature heat, there are potential competitors:

- • district heating fed by waste heat from conventional power stations or from industrial processes.
- • small-scale combined heat and power generation plant
- • heat pumps:



• Heat pumps: A heat pump acts like a "refrigerator", but can also be used in reverse – to heat something rather than cool it. It's mechanism can be described in 4 steps:

1) A cool liquid at low pressure (refrigerant liquid) that boils at low temperature, typically -15 ^{0}C at atmospheric pressure. To make a vapor, energy must be GIVEN by a heat source (called the latent heat of evaporation).

2) The liquid absorbs heat in a heat exchanger, called the evaporator, and vaporizes.

3) The (cold) vapor then enters an electrically driven compressor (energy is added) that raises both its temperature and pressure.

4) The hot vapor then enters another heat exchanger, the condenser, where it condenses to a warm liquid and gives up its latent heat of vaporization.

• Finally it is forced through a fine expansion valve or throttle where it loses pressure. vaporizing and dropping in temperature. The cycle repeats---

To understand the above we MUST remember that we are transferring energy from one place to another!!

2.6 ‘Active’ (some equipment) solar (water and space) heating

History

1890s: A solar water heater was made by simply placing a tank of water behind a window in USA.

1909: The ‘thermosyphon’ had an insulated tank, which could maintain heat over night.

1920: Cheap natural gas was discovered, which made the above units unpopular.

1940s: 80% of Florida homes had solar water heaters, but gave way to cheap fossil fuels.

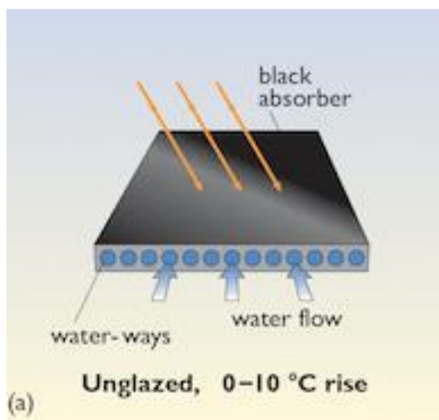
1970s: Commercial solar collectors reappeared, but cheap fossil fuel in the 1990s put negative pressure on them.

2005-2010: Germany & China reestablished collectors and the annual growth approached 16%.

By 2010, 60% of these in China and Japan?.

Solar collectors:

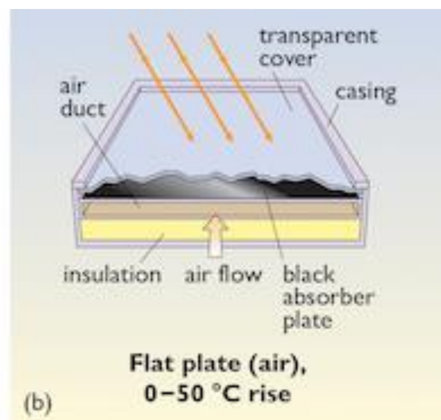
Unglazed: Good for swimming pools where only need to raise temperature a little for comfort.



(a) Unglazed, 0–10 °C rise

Flat plate (air):

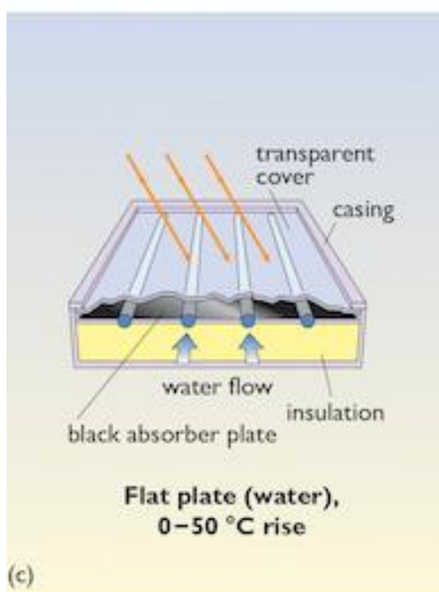
Not as common as water units, and mostly used for crop drying.



(b) Flat plate (air), 0–50 °C rise

Flat plate (water):

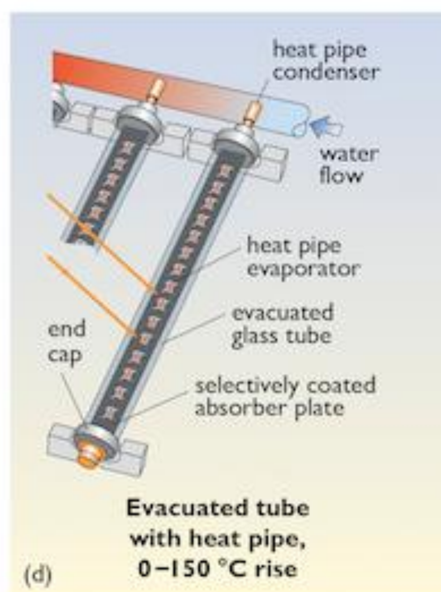
The mainstay of domestic solar water heating outside of China. Sometimes multiple glazes.



(c) Flat plate (water), 0–50 °C rise

Evacuated tube:

The absorber is a metal strip down the center of each tube. Convective losses suppressed by the vacuum. The absorber plate uses a special heat pipe to carry the collected energy to the water.



(d) Evacuated tube with heat pipe, 0–150 °C rise

Robustness, mounting and orientation

- Solar collects are mostly mounted on roofs. They must withstand all types of weather conditions and temperature changes

Active solar space heating and inter-seasonal storage

- Sun energy is not strongly available when most needed, the winter. Some have proposed making huge collectors to collect hot water in the summer and use it later. BUT the storage must be huge and the insulating walls very thick so to make them implacable.

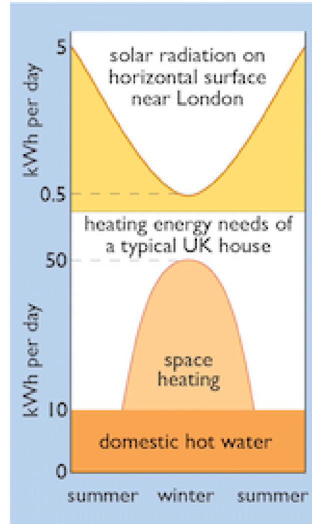
Solar district heating (water AND space)

There are considerable economies in sale of large projects where soar collectors can be purchased and erected in bulk. Since the 1980s "district heating" projects have greatly increased, especially in Sweden, Denmark and Germany. The 18,000 m^2 one below is in Denmark and supplies 30% of the annual heat requirement for the district heating system supplying 1,600 households. Plans are to increase it so as to supply 55% of annual heat requirements.

Below is an illustration and a video clip link about Denmark. ↓

Domestic space heating

• In UK Sun energy is out of phase with need for heat and space heating



• Space heating involves warming the interior spaces of buildings to interior temperatures of approximately 20 ^{0}C.

• However, there is a fundamental problem to do this at high latitudes: the availability of solar radiation is completely out of phase with the overall demand for heat.

• The broad view of passive solar heating is really about the subtle influences of climate on building design. Without this application, it is all too easy to design buildings that are inappropriate to their surroundings.

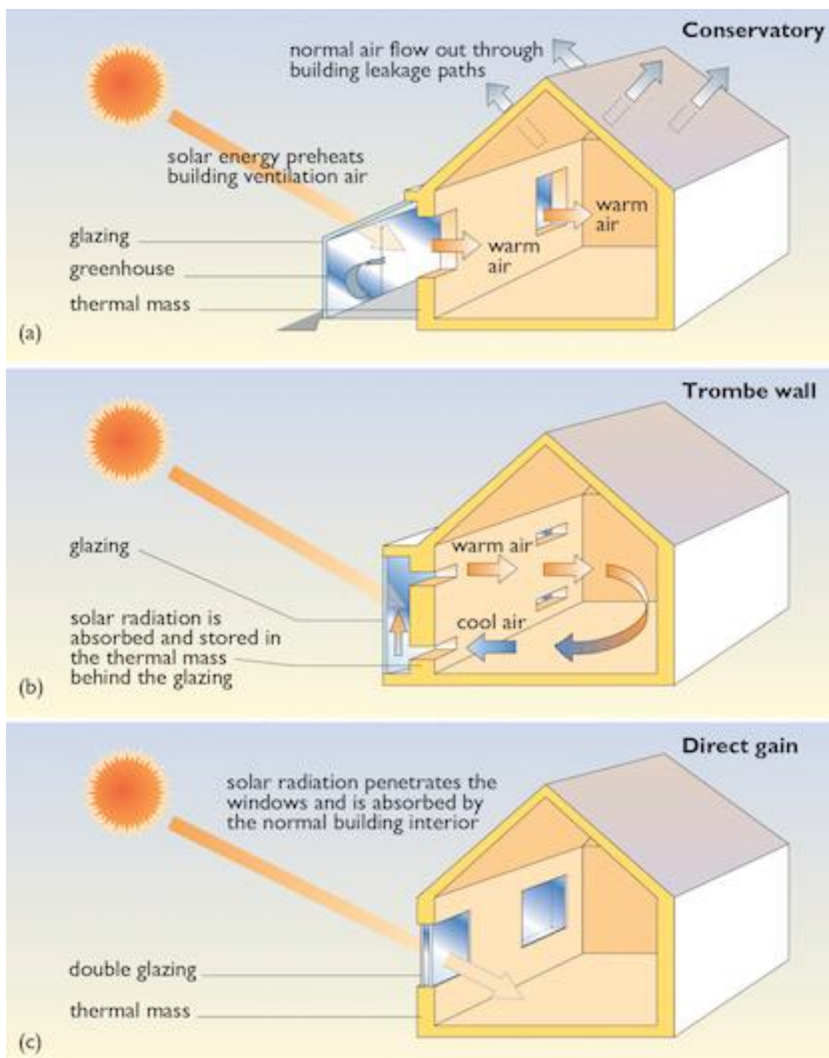
• Active and passive systems BLEND with each other--

Varieties of solar (space) heating system

Conservatory (or "sunspace"):
The "conservatory or "greenhouse" on the south side of a building can be thought of as a habitable solar collector where people live. The energy store is the building itself.

Trombe wall:
The conservatory is replaced by a thin air storage in front of a storage wall. Solar radiation warms the store, the energy of which is radiated into the remainder of the house with an even distribution. At night or on cold days the air flow is cut off.

Direct gain:
The simplest and most common of all passive solar hating systems. All glazed buildings (buildings with windows) make use of this system to some degree.



2.7 Passive solar (space) heating

History

• ALL glazed (windowed) buildings are already to some extent passively solar heated – effectively they are live-in solar collectors.

• The art of making best use of this goes back to the Romans, especially the bath house. Famous example in Pompeii with 2 meter wide and 3 m high glass windows (glazes). Romans invented plate glass!!

• After the fall of Rome, the art of glass window making did not resurface until the 17th century in France - over one thousand years later.

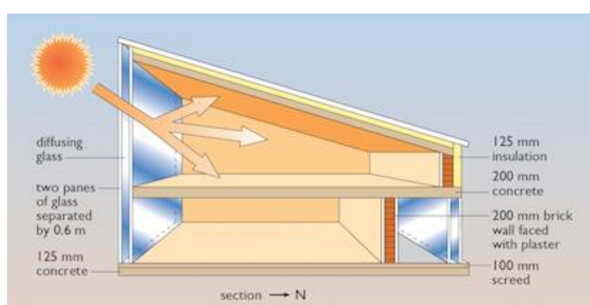
• Even so, the cities of 18th and 19th centuries were overcrowded and the houses ill-lit. It was not until the late 19th century that urban planners sought to design better living conditions.

• They became obsessed with this when it became understood that ultraviolet kills bacteria and viruses, but did not know that UV does not penetrate glass windows. Sunshine and FRESH air became a key idea for society and healthy living. Sunlight in winter also helps to keep the hormones in balance and fight depression.

Direct gain buildings as solar collectors

• Wallasey School building is a classic direct gain design. Has all of the essential features required for passive solar heating:

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



Double panes of *diffusing* glass! Thick walls and insulation.

• Other low-energy buildings were also constructed, like the Wates House in 1975, which was "super-insulated", with quadruple glazing, unusual for the time.

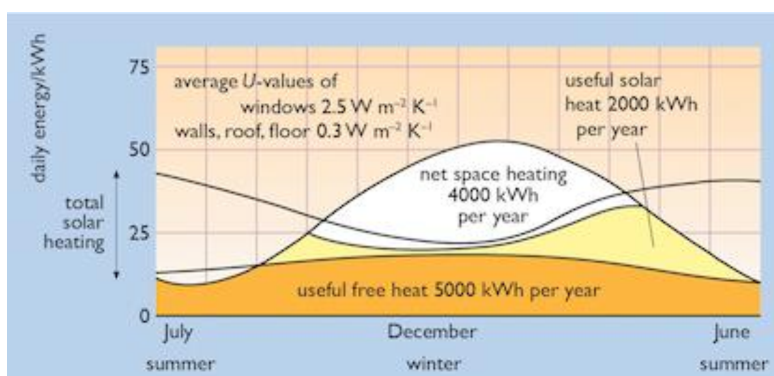
• The art of design for passive solar heating is to understand the energy flows in a building and make the most of them. There must be sufficient energy and lighting, also. *But must be careful against overheating in the summer.*

Window energy balance

• There must be a correct balance of incoming and outgoing energy through the windows/glazing. Must consider:

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

The heating season and free heat gains

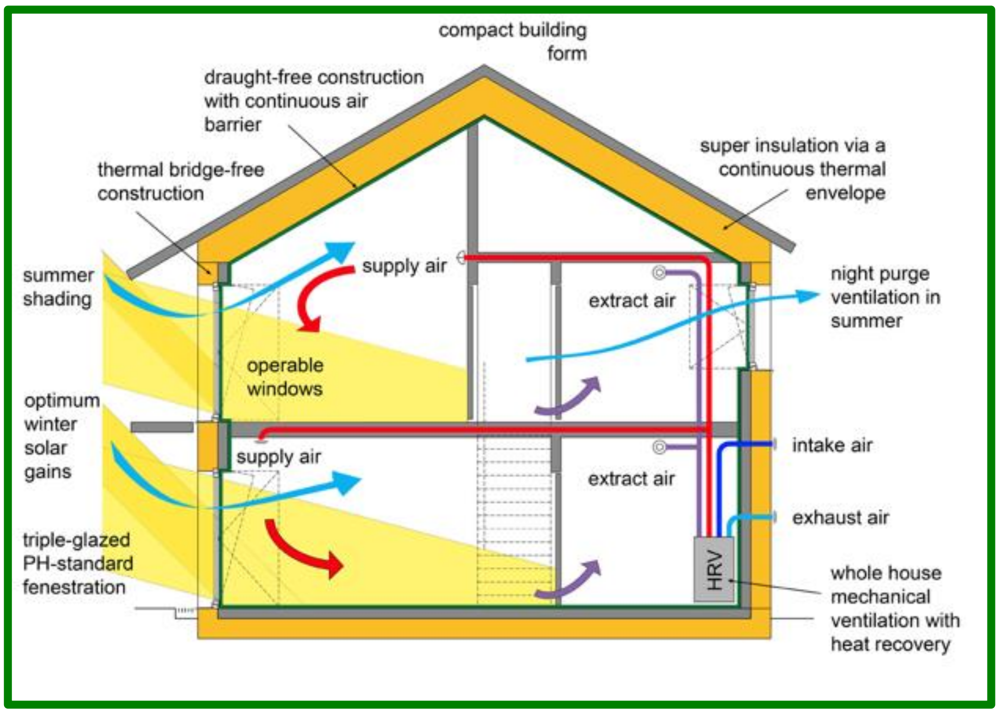


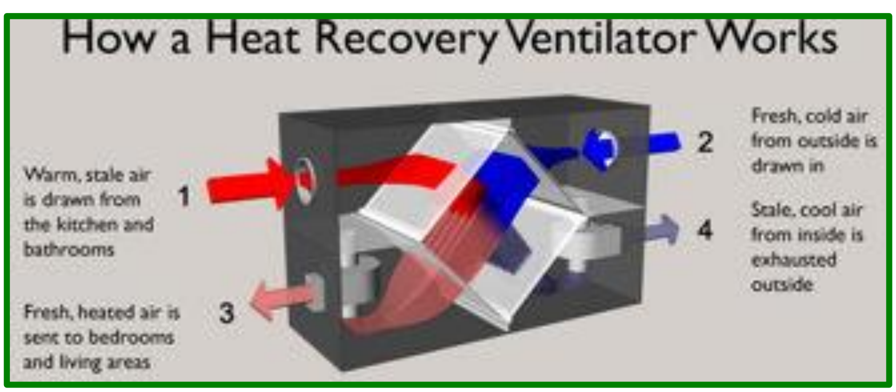
• The total amount of heat that needs to be supplied over one year can be called the gross heating demand, from three sources:

- "free heating gains": body heat of people, heat from cooking, washing, lighting & appliances.
- passive solar gains, mainly through the windows
- fossil fuel energy, from the normal heating system

Passivhaus design

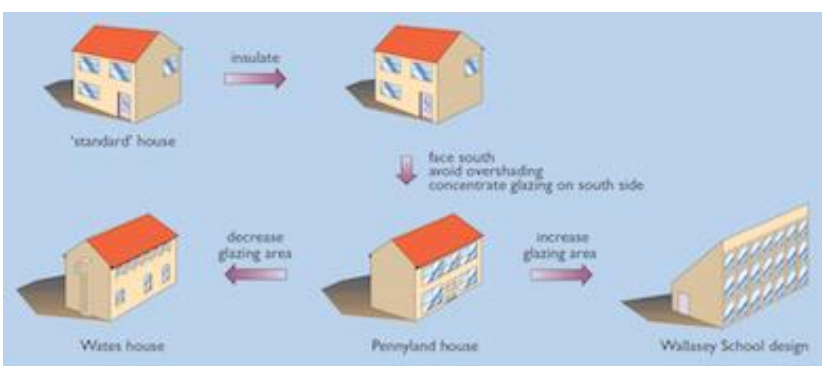
• The Passivhaus design originated in Germany in the 1990s. The house is "passive" in the sense that it does not need a conventional large heating system. It involves using thick insulation, good quality windows and airtight construction to reduce the space heating demand of the building to a low level. It can then be heated mainly by solar gains and heat from appliances and the occupants, themselves. So old buildings have even been retrofitted to incorporate these features.





General passive solar heating techniques
Ch. 11

- There are some basic general guidelines for optimizing the use of passive solar heating in buildings:
  - They should be well-insulated to keep down the overall heat losses
- They should have a responsive, efficient heating system
- The 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, at the north side.
- They should avoid over shading by other buildings in order to benefit from the essential mid-winter sun.
- They should be "thermally massive" to avoid overheating in the summer.



Conservatories, greenhouses and artria

- Right shows: full width

conservatory, thick insulation, and earth sheltering

2.8 Daylighting (houses and buildings)

• Lighting had always been very expensive until the invention of electricity and the electric light bulb, from incandescent, to florescent, to compact florescent, to solid state. In many cities lighting was poor due to crowdedness and other factors.

• Today houses are generally well designed to make use of natural lighting.

• Large office buildings and factories pay about 30% of power costs for lighting. Though may high rises have many windows around the outside, inner spaces are not well lit.

• Though natural lighting can contribute to the heating of buildings, in the summer this becomes a negative factor, especially in buildings that are heavily insulated.

Daylighting: is a combination of energy conservation and passive solar design. It aims to make the most of the natural daylight that is available. 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

• use of task lighting directly over the workplace, rather than lighting the whole building interior (also steerable mirrors, optical fibers and light ducts)

• **BEST Eco-friendly buildings** (Google search)

• **MOST Energy-efficient buildings** (Google search)

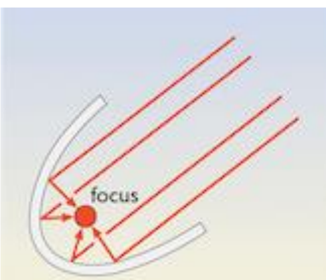
• **FAMOUS Eco-friendly buildings** (Google search)

2.9 Solar thermal engines and electricity generation

In addition to low-temperature applications, it is possible to use mirrors and other devices to concentrate solar energy so as to produced steam, which can power machinery, or even turn turbine-generator systems to produce electricity: concentrating solar power (CSP).

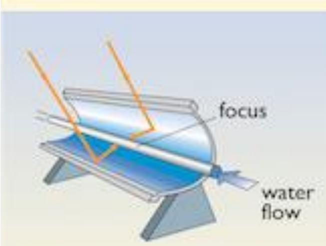
Concerning solar collectors

• Legend has it that in 212 BC Archimedes used the reflective power of polished bronze shields of Greek warriors to set fire to Roman ships besieging the fortress of Syracuse. An experiment in 1973 showed that 60 men each with a mirror 1 m by 1.5 m could indeed ignite a wooden boat at 50 m.



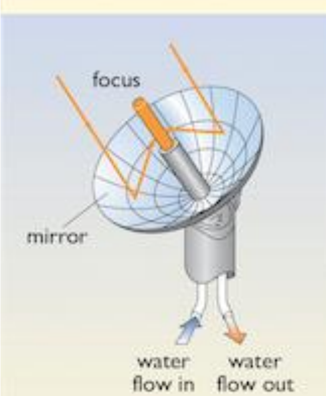
(a) Parabolic mirror brings light to a precise focus in centre

• The most common method of concentrating solar energy is to use a parabolic mirror. All rays of light that enter parallel to the axis of the mirror will be reflected to one point, the focus. However, if they are off axis, they will focus elsewhere. It is therefore ESSENTIAL that the mirror tracks the Sun.



(b) Line focus, 200 – 400 °C

• In the line focus or trough collector the Sun's energy is focused on a pipe running down the center of the trough. Fluid in the pipe as the heat transfer fluid might be mineral oil or other. The trough can be pivoted to track he Sun. (concentration factor of 50)

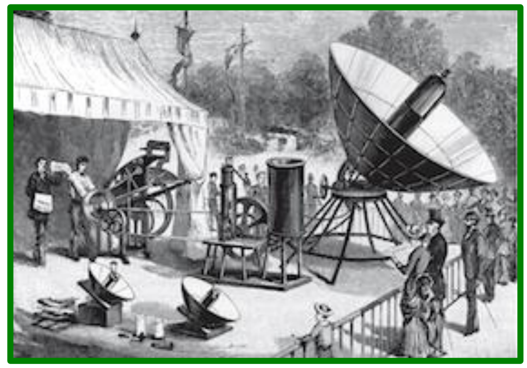


(c) Point focus, >1000 °C

• 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. For optimum the axis must point directly at the Sun, necessitating tracking.

• A line focus parabolic tough collector can produce a temperature of 200-400 ^{0}C; a dish point focus system can produce a temperature of 1,500 ^{0}C (concentration factor of over 1,000)

The first solar engine age



• In the 1860s France lacked a inexpensive supply of coal. Augustin Mouchot creatively designed a series of solar powered machines, including a printing press in the 1870-80s (right). Also solar wine stills, solar cookers, and even solar engines driving refrigerators. Although clever, suffered from low power density and overall efficiency. Big problem was that the devices could not provide sufficiently high temperatures.

• *Could not compete with new supplies of coal in the 1890s owing to increased investment in mines and railways.*

• At beginning of the 20th century USA entrepreneur determines strong Sun necessary, so conducted experimenting Egypt with HUGE mirror (20,000 square miles). Some envisioned HUGE collectors in the Sahara!!

• BUT then came WWI, and immediately afterwards the era of CHEAP OIL. Interest in solar energy collapsed and remained dormant -----

• A KEY point is that for any machine using heat to be efficient the efficiency is proportional to the difference in temperature between the input and output. Thus the steam engine was not effective until the invention of the condenser, which was to cool the output region while making the difference much larger.

The new solar age

• In the mid 1900s some entrepreneurs envisioned "power towers" where solar energy could be collected from various types of solar mirrors. This would heat some fluid like mineral oil or molten salt, which could give to water in a heat exchanger, which could run a turbine and generator. Very high temperatures were potentially available.

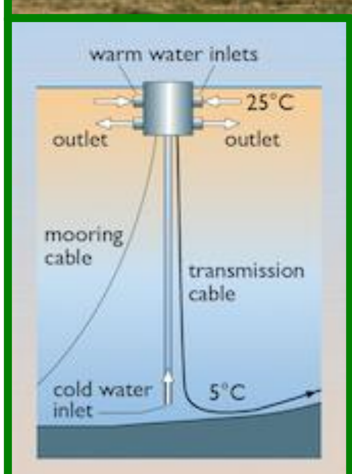
• Power towers: In the 1980 the first, serious, large, experimental solar thermal electricity generation schemes (were built to make use of high temperatures - known as concentrating solar power (GSP) plants. A 10 megawatt (MW) plant, Solar One was built in California in 1981 and rebuilt in 1995 as Solar Two. Operated with molten salt at 500 ^{0}C. Included heat storage so could produce electricity 24 hours per day

11 MW Planta Solar 10 in Seville, Spain. Limited storage and natural gas backup.

Luz International plant in California. Solar Electricity Energy System (SEGS). Heat synthetic oil to 390 ^{0}C. Competitive with PV.

Backed up regular plants for overflow times. Planed to make more, but fuel costs decreased. California plans 33% of it electricity from alternative energy by 2020

Here is an array of 60 parabolic dishes each with a 25 kW Stirling engine apparatus, which can operate at very high temperatures, up to 1,000 ^{0}C, which will result in high efficiency, constructed in Arizona in 2010



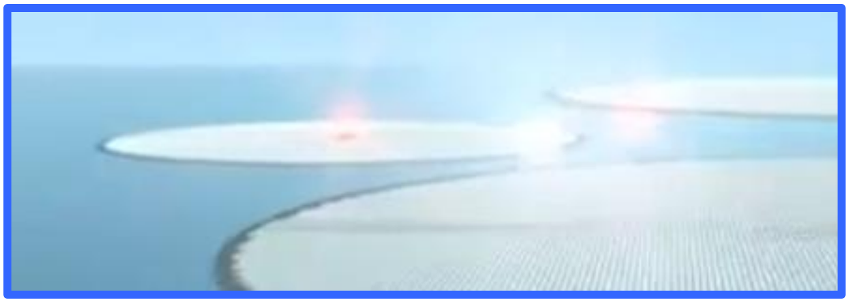
- Solar ponds, using salty lakes. Difficult with disadvantages.

• Plan to use differences in temperature between upper and lower levels of ocean to power a heat pump. But difficult.

• Solar updraft tower devices have been tested, using a huge greenhouse like collection area. Convection currents rise in a very large tower of about 1 k. Rising convection currents turn a turbine and generator. But huge area needed and difficult. Still testing.

Chinese type hot water heater.

Solar islands:



• Everything depends on location with related appropriate technology