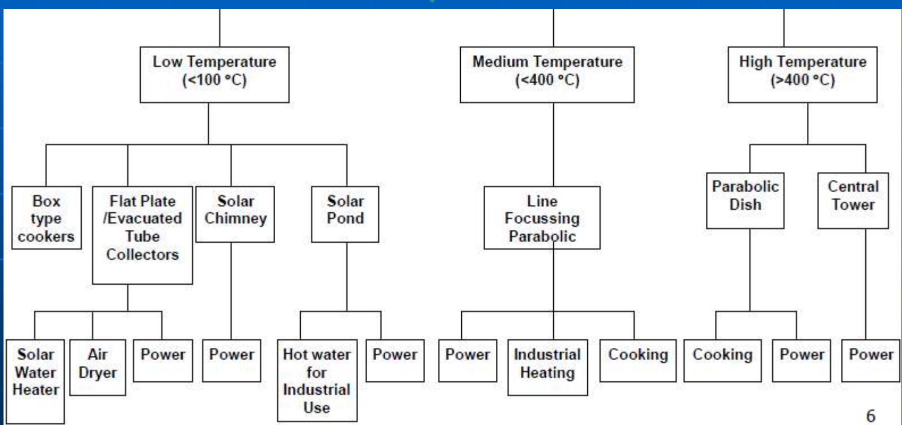
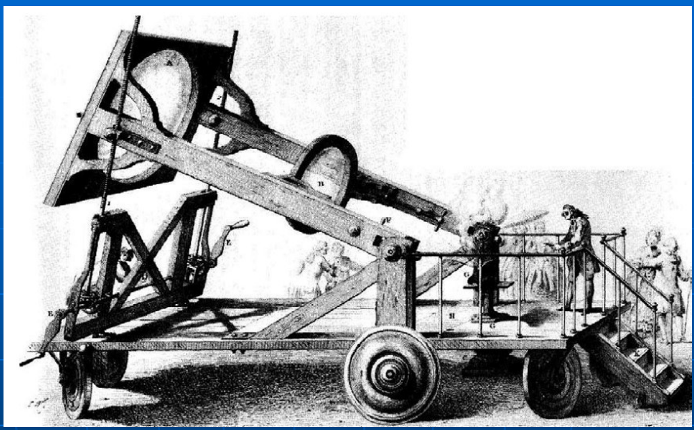
Solar Thermal Systems

Solar Thermal



History…

- Very first applications of solar energy refer to the use of concentrating collectors
- During the 18th century, solar furnaces capable of melting iron, copper, and other metals were being constructed of polished iron, glass lenses, and mirrors
- The furnaces were in use throughout Europe and the Middle East
- One of the first large-scale applications was the solar furnace built by the well known French chemist Lavoisier, who, around 1774, constructed powerful lenses to concentrate solar radiation



Solar furnace used by Lavoisier in 1774

- Attained a temperature of 1750°C
- The furnace used a 1.32 m lens plus a secondary 0.2 m lens

Solar Energy Collectors

- Solar energy collectors are special kinds of heat exchangers that transform solar radiation energy to internal energy of the transport medium
- The major component of any solar system is the solar collector
- This is a device that absorbs the incoming solar radiation, converts it into heat, and transfers the heat to a fluid (usually air, water, or oil) flowing through the collector
- Directly used or transferred to a thermal energy storage tank, from which it can be drawn for use at night or on cloudy days

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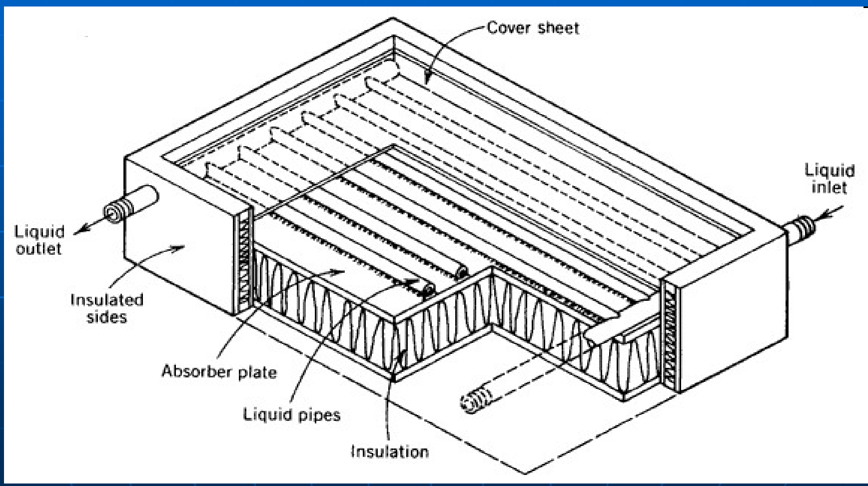
- There are basically two types of solar collectors: non-concentrating (flat plate) and concentrating
- A non-concentrating collector has the same (almost!) area for intercepting and absorbing solar radiation
- A concentrating solar collector usually has concave reflecting surfaces to intercept and focus the sun's beam radiation to a smaller receiving area
- Concentrating collectors are suitable for high-temperature applications
- Solar collectors can also be distinguished by the type of heat transfer liquid used (water, non-freezing liquid, air, or heat transfer oil)

Flat plate collector



- The basic parts are a full-aperture absorber, transparent or translucent cover sheets, and an insulated box
- The absorber is usually a sheet of high-thermal-conductivity metal with tubes or ducts either integral or attached
- Its surface is painted or coated to maximize radiant energy absorption and in some cases to minimize radiant emission
- The cover sheets, called glazing, let sunlight pass through to the absorber but insulate the space above the absorber to prohibit cool air from flowing into this space
- The insulated box provides structure and sealing and reduces heat loss from the back or sides of the collector

Absorber plate

- absorb the maximum possible amount of solar irradiance, conduct this heat into the working fluid at a minimum temperature difference, and lose a minimum amount of heat back to the surroundings
- To maximize the energy collection, the absorber of a collector should have a coating that has high absorptance for solar radiation (short wavelength) and a low emittance for re-radiation (long wave length)
- Such a surface is referred as a **selective surface**
- The absorptance of the collector surface for shortwave solar radiation depends on the nature and color of the coating and on the incident angle
- Usually black color is used

Collector construction

- For fluid-heating collectors, passages must be integral with or firmly bonded to the absorber plate
- A major problem is obtaining a good thermal bond between tubes and absorber plates without incurring excessive costs for labor or materials
- The materials most frequently used for collector plates are copper, aluminum, and stainless steel
- UV-resistant plastic extrusions are used for low-temperature applications

Solar Thermal Applications

Low Temperature (< 100°C)

- Domestic water and space heaters
- Swimming pool heating
- Ventilation air preheating

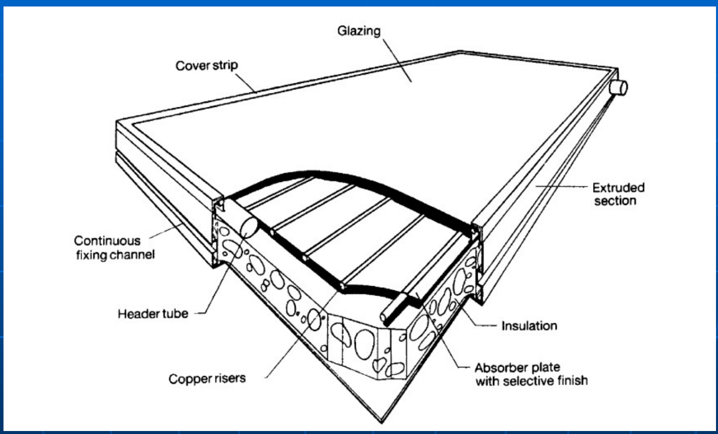
Medium Temperature (100°C – 400°C)

- Commercial cafeterias, laundries, hotels
- Industrial process heating

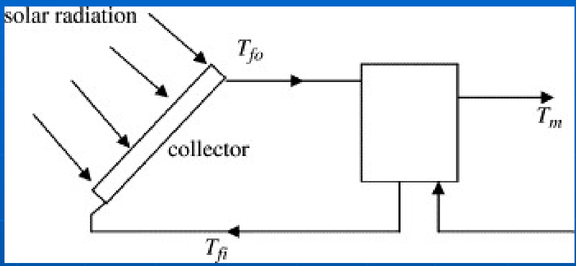
High Temperature (> 400°C)

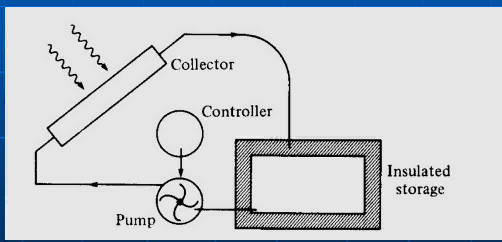
- Industrial process heating
- Electricity generation

Solar Water Heating



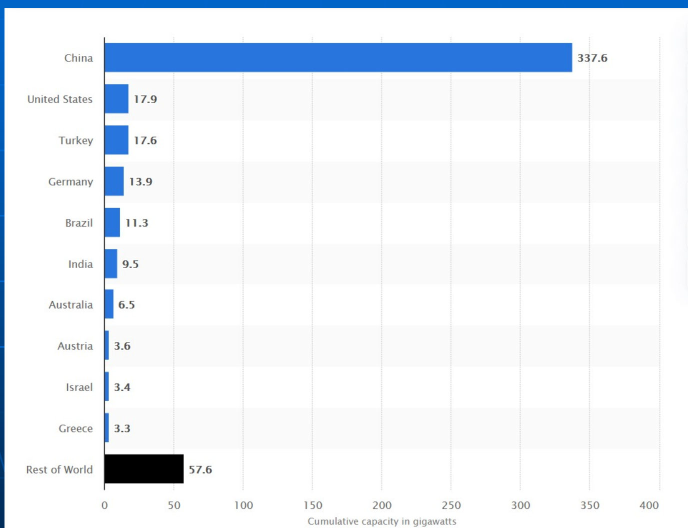
Flat Plate Collector



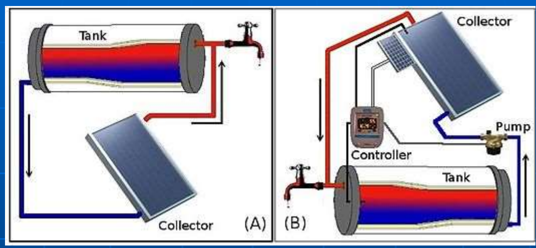


Collector coupled to a separate storage tank by a pump

World wide solar water heating installations

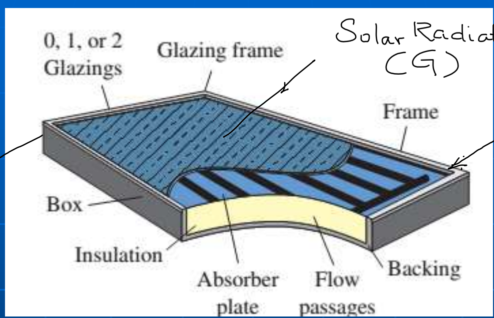


Direct Systems



Passive Active

Performance of Solar Collector



Solar Radiation (G)

Water In ($T_{w,in}$)

Water out ($T_{w,out}$)

The rate of solar heat absorbed by the absorber plate is

$$\dot{Q}_{\text{abs}} = \tau\alpha AG$$

absorptivity

transmissivity

Heat is lost from the collector by convection to the surrounding air and by radiation to the surrounding surfaces and sky, and it can be expressed as

$$\dot{Q}_{\text{loss}} = UA(T_c - T_a)$$

Collector temperature

Ambient temperature

Collector loss coefficient (W/m²·K)

$$\begin{aligned}\dot{Q}_{\text{useful}} &= \dot{Q}_{\text{abs}} - \dot{Q}_{\text{loss}} \\ &= \tau\alpha AG - UA(T_c - T_a) \\ &= A[\tau\alpha G - U(T_c - T_a)]\end{aligned}$$

Water inlet temp.

Water outlet temp

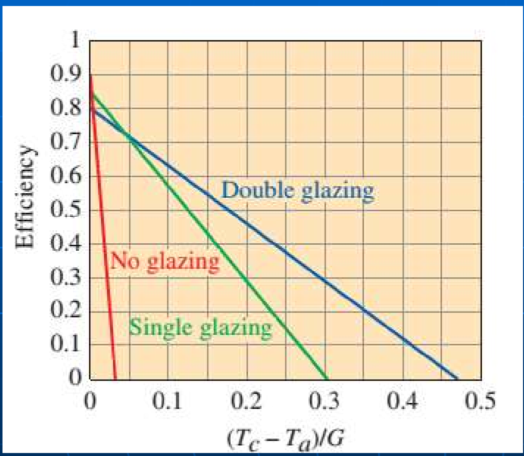
$$\dot{Q}_{\text{useful}} = \dot{m}c_p(T_{w,\text{out}} - T_{w,\text{in}})$$

$\dot{m}$ = mass flow rate of water (kg/s)

c_p = Specific heat of water (kJ/kg.K)

4.18 kJ/kg.K

$$\eta_c = \frac{\dot{Q}_{\text{useful}}}{\dot{Q}_{\text{incident}}} = \frac{\tau\alpha AG - UA(T_c - T_a)}{AG} = \tau\alpha - U\frac{T_c - T_a}{G}$$



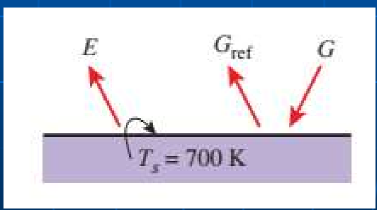
	$\tau\alpha$	U, W/m²·°C
No glazing	0.90	28
Single glazing	0.85	2.8
Double glazing	0.80	1.7

Hottel-Whillier-Bliss equation

$$\eta_c = F_R \tau\alpha - F_R U \frac{T_{w,\mathrm{in}} - T_a}{G}$$

$$\eta_c = F_R K_{\tau\alpha} \tau\alpha - F_R U \frac{T_{w,\mathrm{in}} - T_a}{G}$$

An opaque horizontal plate is well insulated on the edges and the lower surface. The irradiation on the plate is 2500 W/m^2, of which 800 W/m^2 is reflected. The plate has a uniform temperature of 700 K and has an emissive power of 9000 W/m^2. Determine the total emissivity and absorptivity of the plate.



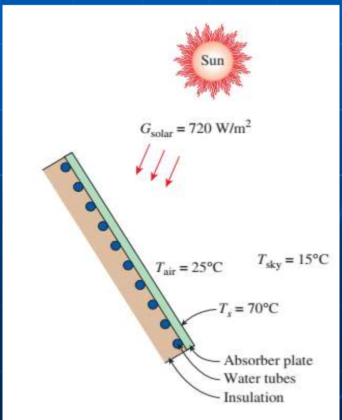
$$\varepsilon = \frac{E}{E_b} = \frac{E}{\sigma T_s^4} = \frac{9000 \text{ W/m}^2}{(5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4)(700 \text{ K})^4} = \mathbf{0.661}$$

$$\alpha + \rho + \tau = 1 \rightarrow \alpha = 1 - \rho \qquad \text{(for opaque surface, } \tau = 0\text{)}$$

$$\rho = \frac{G_{\text{ref}}}{G} = \frac{800 \text{ W/m}^2}{2500 \text{ W/m}^2} = 0.320$$

$$\alpha = 1 - 0.320 = \mathbf{0.680}$$

The absorber surface of a solar collector is made of aluminum coated with black chrome (absorptivity = 0.87 and emissivity = 0.09). Solar radiation is incident on the surface at a rate of 720 W/m^2. The air and the effective sky temperatures are 25 and 15°C, respectively, and the convection heat transfer coefficient is 10 W/m^2·K. For an absorber surface temperature of 70°C, determine the net rate of solar energy delivered by the absorber plate to the water circulating behind it.



$$\dot{q}_{\text{net}} = \dot{q}_{\text{gain}} - \dot{q}_{\text{loss}}$$

$$\dot{q}_{\text{net}} = \alpha_s G_{\text{solar}} - [\varepsilon\sigma(T_s^4 - T_{\text{sky}}^4) + h(T_s - T_{\text{air}})]$$

$$\dot{q}_{\text{net}} = 0.87(720\ \text{W/m}^2) - 0.09(5.67\times10^{-8}\ \text{W/m}^2\cdot\text{K}^4)[(70+273\ \text{K})^4 - (15+273\ \text{K})^4]$$
$$- (10\ \text{W/m}^2\cdot\text{K})(70°\text{C} - 25°\text{C})$$
$$= \mathbf{141\ W/m^2}$$

The specifications of two flat-plate collectors are given as follows:

Single glazing: $\tau = 0.96$, $\alpha = 0.96$, $U = 9\ \text{W/m}^2\cdot°\text{C}$

Double glazing: $\tau = 0.93$, $\alpha = 0.93$, $U = 6.5\ \text{W/m}^2\cdot°\text{C}$

The heat removal factor for both collectors is 0.95, the solar insolation is 550 W/m^2, and the ambient air temperature is 23°C. For each collector, determine (a) the collector efficiency when the water enters the collector at 45°C, (b) the temperature of water at which the collector efficiency is zero, and (c) the maximum collector efficiency.

a

Single glazing:

$$\eta_c = F_R K_{\tau\alpha} \tau\alpha - F_R U \frac{T_{w,\text{in}} - T_a}{G}$$
$$= (0.95)(1)(0.96)(0.96) - (0.95)(9\ \text{W/m}^2\cdot{}^\circ\text{C})\frac{45^\circ\text{C} - 23^\circ\text{C}}{550\ \text{W/m}^2}$$
$$= \mathbf{0.534}$$

Double glazing:

$$\eta_c = F_R K_{\tau\alpha} \tau\alpha - F_R U \frac{T_{w,\text{in}} - T_a}{G}$$
$$= (0.95)(1)(0.93)(0.93) - (0.95)(6.5\ \text{W/m}^2\cdot{}^\circ\text{C})\frac{45^\circ\text{C} - 23^\circ\text{C}}{550\ \text{W/m}^2}$$
$$= \mathbf{0.575}$$

b

Single glazing:

$$F_R K_{\tau\alpha} \tau\alpha - F_R U \frac{T_{w,\text{in}} - T_a}{G} = 0$$
$$F_R K_{\tau\alpha} \tau\alpha = F_R U \frac{T_{w,\text{in}} - T_a}{G}$$
$$(0.95)(1)(0.96)(0.96) = (0.95)(9\ \text{W/m}^2\cdot{}^\circ\text{C})\frac{T_{w,\text{in}} - 23^\circ\text{C}}{550\ \text{W/m}^2} = 0$$
$$T_{w,\text{in}} = \mathbf{79.3^\circ C}$$

Double glazing:

$$F_R K_{\tau\alpha} \tau\alpha = F_R U \frac{T_{w,\text{in}} - T_a}{G}$$
$$(0.95)(1)(0.93)(0.93) = (0.95)(6.5\ \text{W/m}^2\cdot{}^\circ\text{C})\frac{T_{w,\text{in}} - 23^\circ\text{C}}{550\ \text{W/m}^2} = 0$$
$$T_{w,\text{in}} = \mathbf{96.2^\circ C}$$

c

Collector A: $\eta_{c,\max} = F_R K_{\tau\alpha} \tau\alpha = (0.95)(1)(0.96)(0.96) = \mathbf{0.876}$

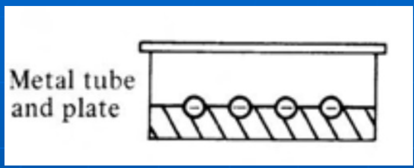
Collector B: $\eta_{c,\max} = F_R K_{\tau\alpha} \tau\alpha = (0.95)(1)(0.93)(0.93) = \mathbf{0.822}$

A solar collector provides the hot water needs of a family for a period of 7 months except for 5 months of winter season. The collector supplies hot water at an average temperature of 55°C and the average temperature of cold water is 18°C. The family uses an average of 15 tons of hot water from the solar collector per month. An electrical resistance heater supplies hot water in winter months. The cost of electricity is Rs. 7/kWh and the efficiency of the electric heater can be taken to be 93 percent considering heat losses from the system. Determine the annual electricity and cost savings to this family due to solar collector.

$$Q = mc_p(T_1 - T_2) = (15{,}000 \text{ kg/month})(4.18 \text{ kJ/kg}\cdot°\text{C})(55-18)\,°\text{C} = 2.320 \times 10^6 \text{ kJ/month}$$

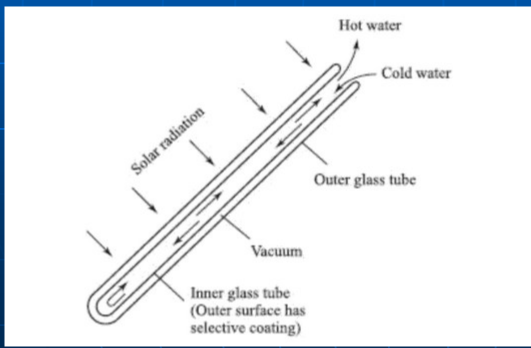
$$\text{Electricity savings} = \frac{Q}{\eta_{\text{heater}}} = (7 \text{ months})\frac{(2.320 \times 10^6 \text{ kJ/month})}{0.93}\left(\frac{1 \text{ kWh}}{3600 \text{ kJ}}\right) = \mathbf{4850\,kWh}$$

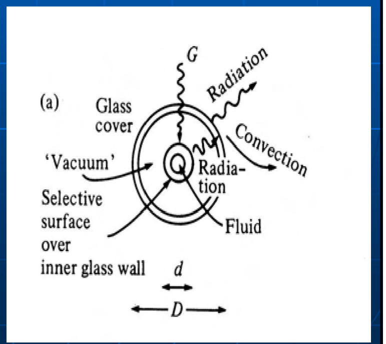
Evacuated Tube Collector



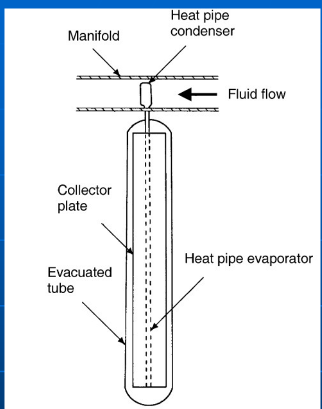
Flat plate collector

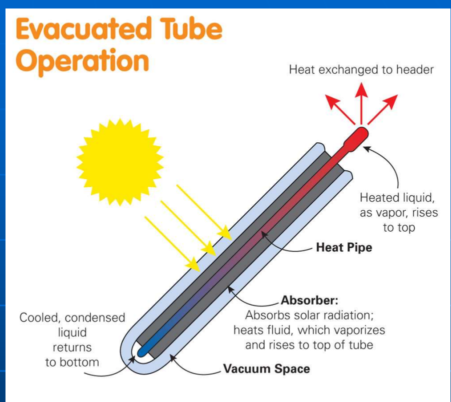
To reduce convective heat loss





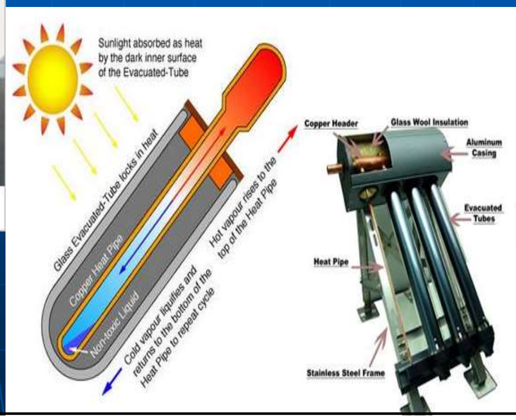
Evacuated Tube Collector



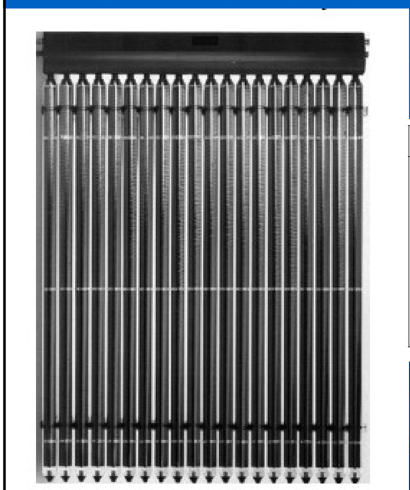


- Heat pipe inside a vacuum-sealed tube
- Sealed copper pipe is attached to a black copper fin that fills the tube (absorber plate)
- Protruding from the top of each tube is a metal tip attached to the sealed pipe (condenser)

ETC Based Water Heating System

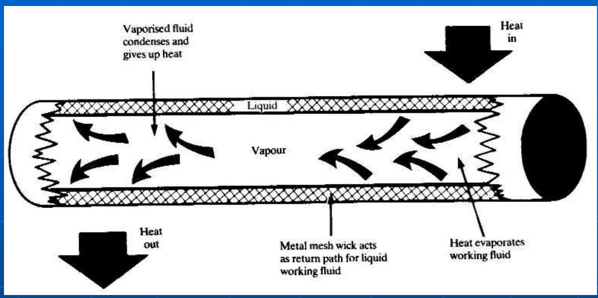


Actual ETC Installation



Parameter	Value
Glass tube diameter	65 mm
Glass thickness	1.6 mm
Collector length	1965 mm
Absorber plate material	Copper
Coating	Selective
Absorber area	0.1 m^2

Heat Pipe



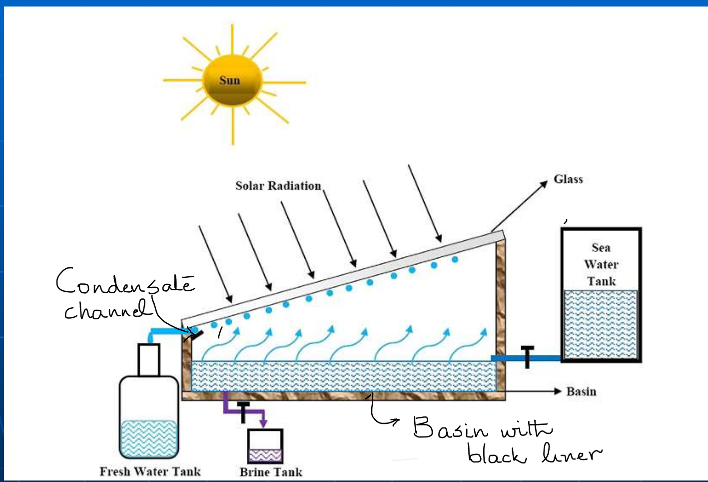
➢ The heat pipe comprises of three elements: a sealed container, a capillary wick structure and a working fluid

➢ The capillary wick structure is integrally fabricated into the interior surface of the container tube and sealed under vacuum

Heat Pipe Operation

- Heat pipes employ evaporative cooling to transfer thermal energy from one point to another by the evaporation and condensation of the coolant
- The condensed working fluid flows back to the hot end of the pipe
- In the case of vertically-oriented heat pipes the fluid may be moved by the force of gravity
- In the case of heat pipes containing wicks, the fluid is returned by capillary action

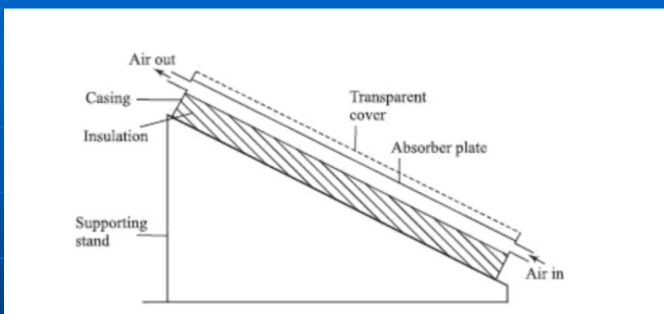
Solar Desalination



Typical Yield: 3 l/m² per day

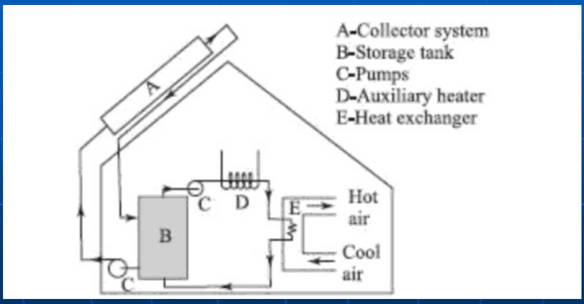
35

Solar Air Heater



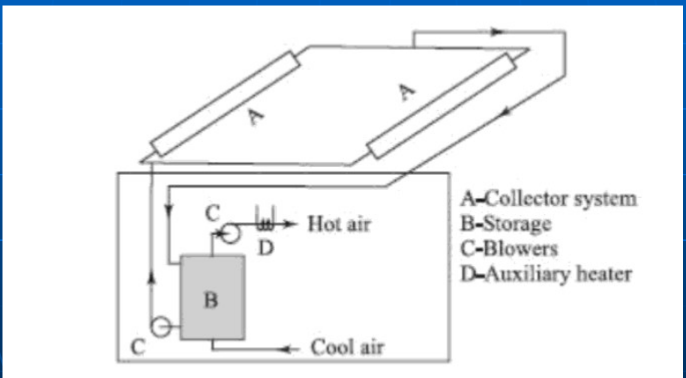
Space Heating Applications

Active System using Liquid Flat Plate Collectors



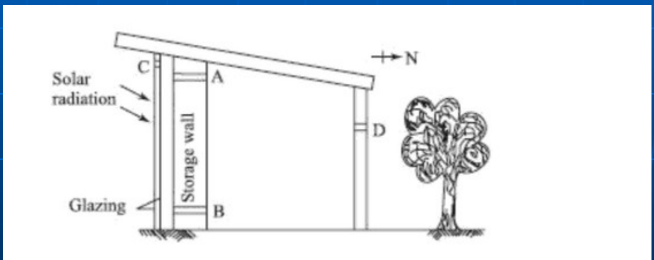
Space Heating Applications

Active System using Air Heaters

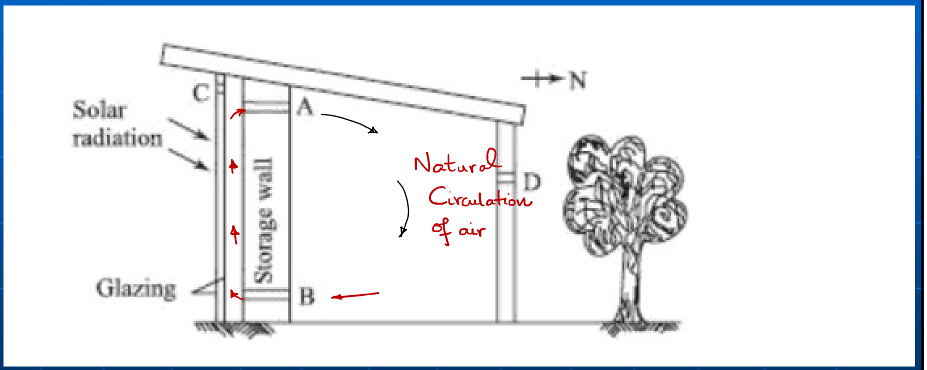


Trombe Wall

For passive space heating and summer ventilation

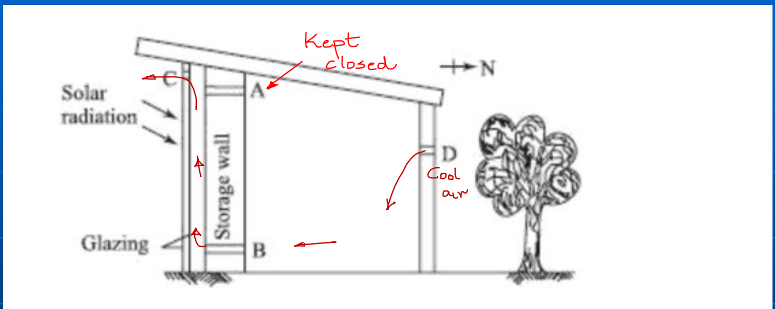


Space Heating



→ The vents A and B are kept open in the day
→ They are kept closed during the night

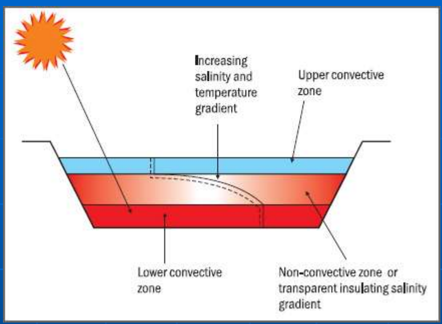
Summer Ventilation

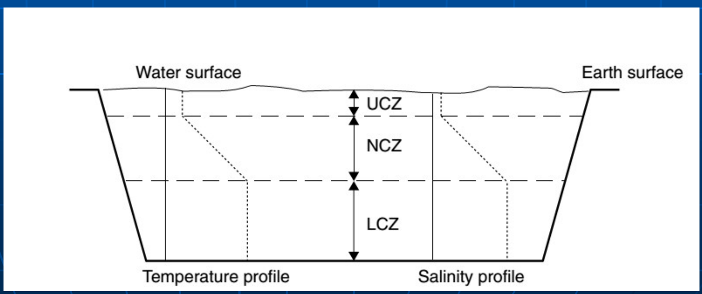


→ During the day, the vent A is kept closed

→ The vents D, B and C are kept open

Solar Pond

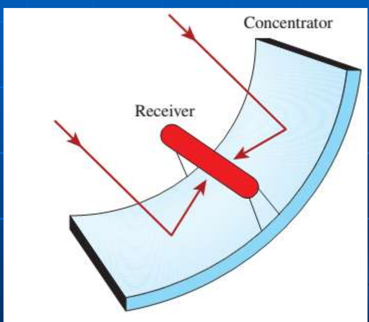




- A salt gradient solar pond is a body of saline water in which the salt concentration increases with depth, from a very low value at the surface to near saturation at the depth of usually 1–2 m
- A stagnant, highly transparent insulating zone is created in the upper part of the pond to contain the hot fluid in the lower part of the pond
- In a non-conventional solar pond, part of the incident insolation is absorbed and converted to heat, which is stored in the lower regions of the pond
- Solar ponds are both solar energy collectors and heat stores

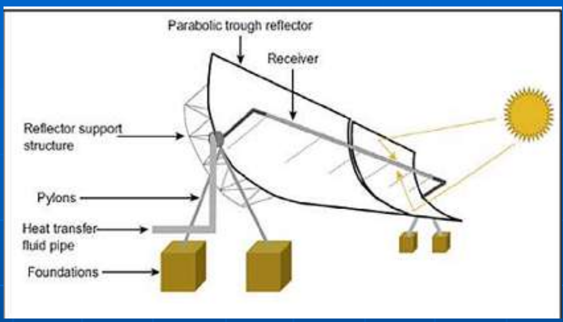
Solar Concentrators

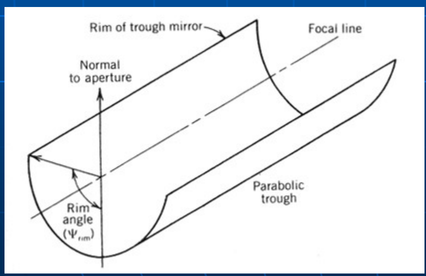
- Hot fluid (water, steam, air, or another fluid) at higher temperatures can be produced using concentrating collectors-by concentrating solar radiation on a smaller area

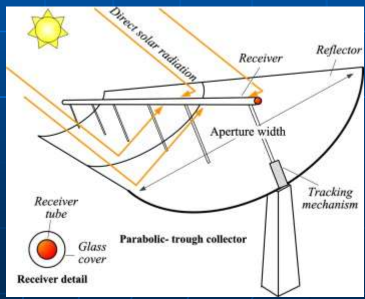


$$CR = \frac{A_a}{A_r}$$

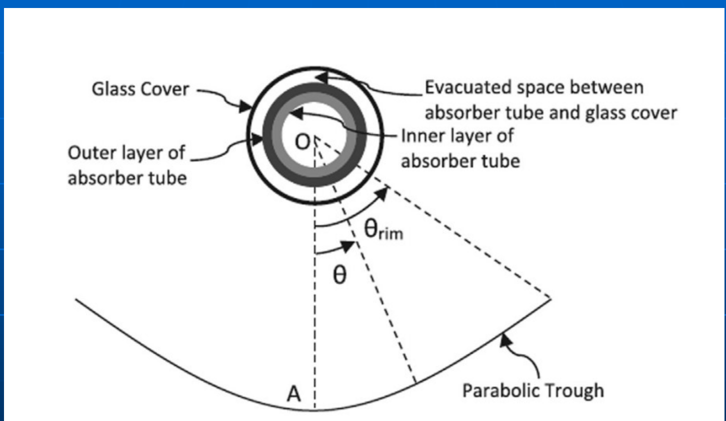
• Energy delivery temperatures can be increased by decreasing the area from which the heat losses occur





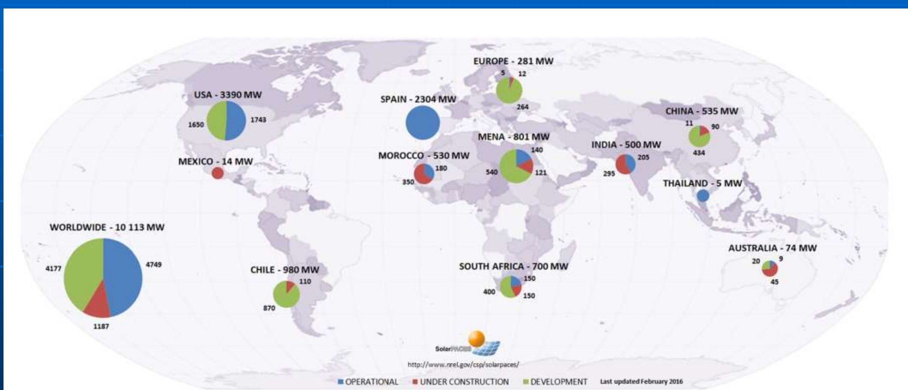


Cross sectional view of the receiver tube

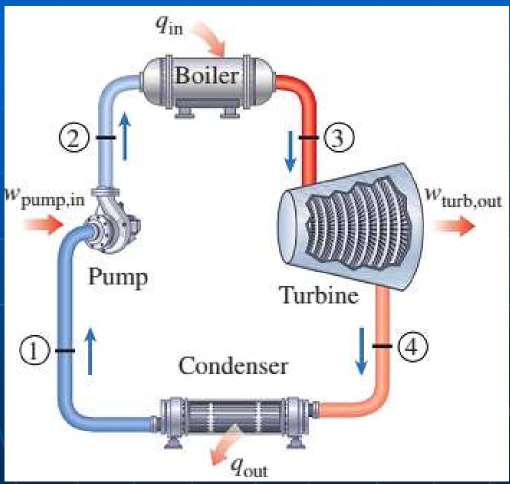


Parameter	Value/type
Collector rim angle	70°
Reflective surface	Silvered acrylic
Receiver material	Steel
Collector aperture	2.3 m
Receiver surface treatment	Highly selective blackened nickel
Absorptance	0.97
Emittance (80°C)	0.18
Glass envelope transmittance	0.96
Absorber outside diameter	50.8 mm
Tracking mechanism accuracy	0.05°
Collector orientation	Axis in N-S direction
Mode of tracking	E-W horizontal

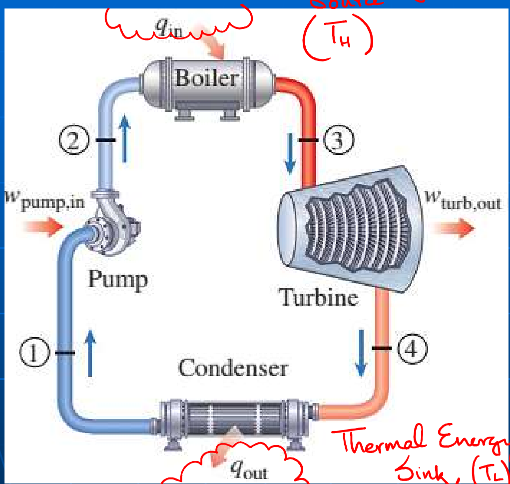
CSP Plants



Thermal Power Cycle



Thermal Energy Source (T_H)



Thermal Energy Sink, (T_L)

$$\omega_{net} = \omega_{turb,out} - \omega_{pump,in}$$

Thermal Efficiency:

$$\eta_{th} = \frac{\omega_{net}}{q_{in}}$$

for the cycle,

$$\omega_{net} = q_{net}$$

$$= q_{in} - q_{out}$$

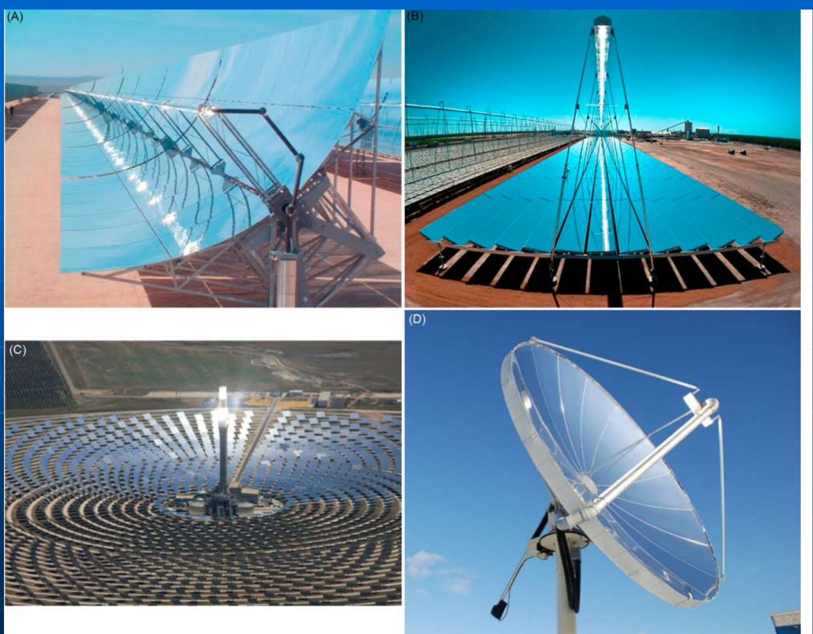
$$\therefore \eta_{th} = 1 - \frac{q_{out}}{q_{in}}$$

$$\eta_{max} = 1 - \frac{T_L}{T_H}$$

(Carnot Efficiency)

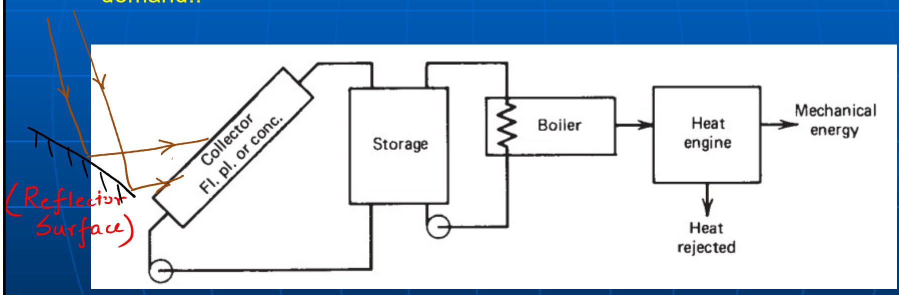
Motion	Collector type	Absorber type	Concentration ratio	Indicative temperature range (°C)
Stationary	Flat-plate collector (FPC)	Flat	1	30–80
	Evacuated tube collector (ETC)	Flat	1	50–200
	Compound parabolic collector (CPC)	Tubular	1–5	60–240
Single-axis tracking			5–15	60–300
	Linear Fresnel reflector (LFR)	Tubular	10–40	60–250
	Cylindrical trough collector (CTC)	Tubular	15–50	60–300
	Parabolic trough collector (PTC)	Tubular	10–85	60–400
Two-axis tracking	Parabolic dish reflector (PDR)	Point	600–2000	100–1500
	Heliostat field collector (HFC)	Point	300–1500	150–2000

Note: Concentration ratio is defined as the aperture area divided by the receiver/absorber area of the collector.



Solar Thermal Power System

The use of approximately 1% of the surface area of the Sahara for solar power plants would be sufficient to meet the entire global electricity demand!!

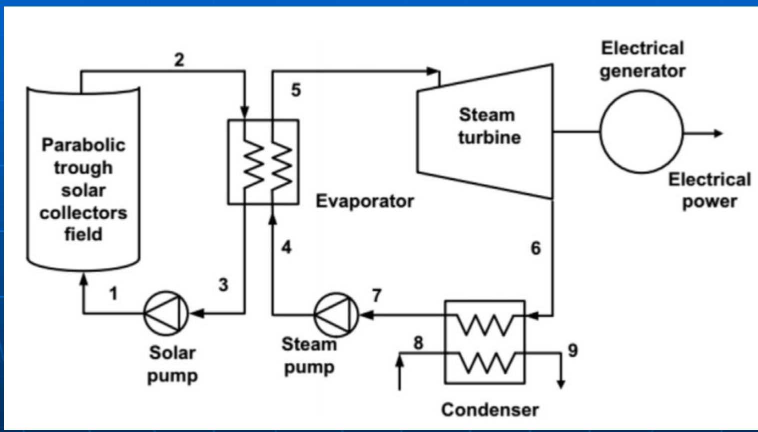


In a solar thermal power generation system the thermal energy source is the solar collector

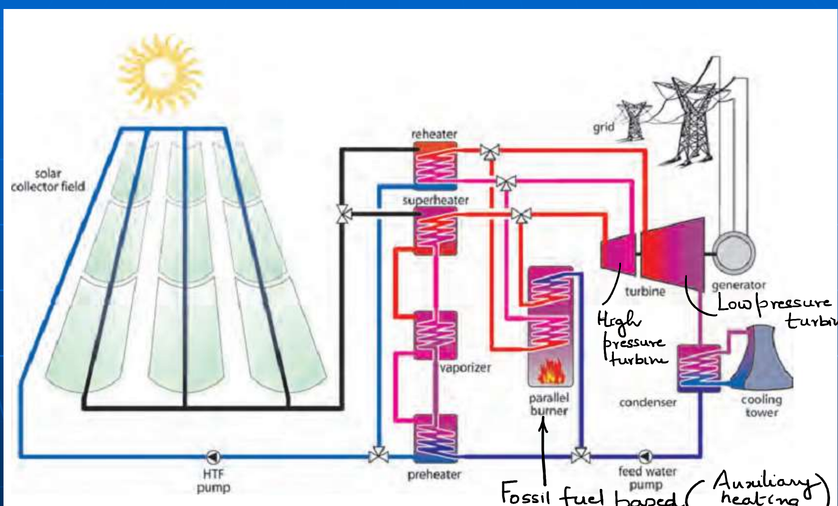
Parabolic Trough Collector Details

Collector type	LS-1	LS-2	LS-3	EuroTrough
Year of first installation	1984	1986	1988	2001
Concentration ratio	61	61	82	82
Aperture width (m)	2.5	5.0	5.76	5.76
Collector length (m)	50	48	99	150
Aperture (m^2)	128	235	545	825
Absorber tube diameter (mm)	42.4	70	70	70

Schematic of solar thermal power plant



Solar Electric Generation Systems



Fossil fuel based (Auxiliary heating)

HTF : Heat Transfer Fluid

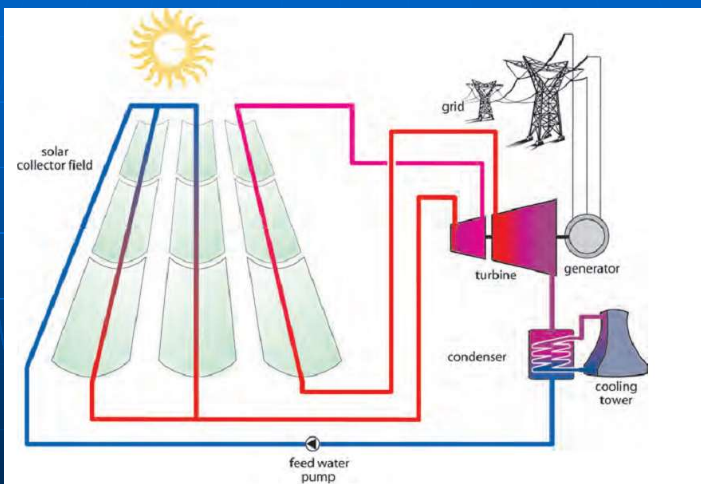
Technical details of SEGS

Plant	I	II	III	IV	V	VI	VII	VIII	IX
Year of commissioning	1984	1985	1986	1986	1986	1988	1988	1989	1990
Net capacity (MW)	13.8	30	30	30	30	30	30	80	80
Land use (1000 m^2)	290	660	800	800	860	660	680	1620	1690
Aperture (1000 m^2)	83	165	233	233	251	188	194	464	484
HTF outlet temp. (°C)	306	321	349	349	349	391	391	391	391
Efficiency (%)									
– Steam turbine (solar)	31.5	29.4	30.6	30.6	30.6	37.6	37.6	37.6	37.6
– Steam turbine (gas)	–	37.3	37.3	37.3	37.3	39.5	39.5	37.6	37.6
– Solar field (thermal)[a]	35	43	43	43	43	43	43	53	50
– Solar-to-electric (net)[a]	9.3	10.6	10.2	10.2	10.2	12.4	12.3	14.0	13.6
Specific invest. costs (US$/kW)	4490	3200	3600	3730	4130	3870	3870	2890	3440

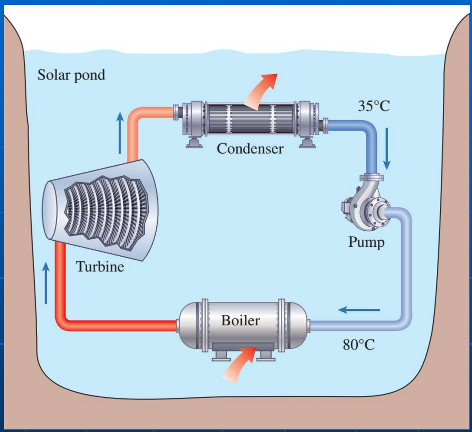
[a] Design

The levelized electricity costs have decreased with US$0.26/kWh for the first SEGS plant down to US$0.12–0.14/kWh for the plants that were erected last!

Direct Steam Generation



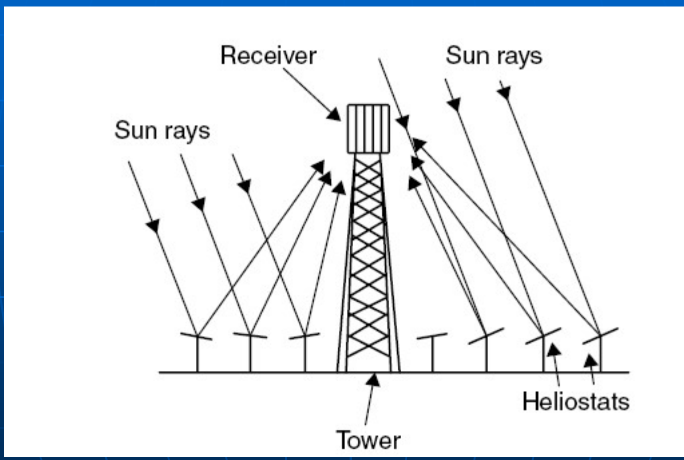
Solar Pond based Power Generation System



$$\eta_{\text{th,max}} = 1 - \frac{T_L}{T_H} = 1 - \frac{(35 + 273)\text{ K}}{(80 + 273)\text{ K}} = 0.127 \text{ or } 12.7 \text{ percent}$$

Paraboloid Dish Reflector

Central Receiver System



- The Gemasolar power plant located in Seville, Spain consists of 2650 heliostats that focus 95 percent of solar radiation onto a giant receiver
- The plant started commercial operation in 2011 occupying a field of 185 hectares
- A temperatures of 900ºC is obtained at the receiver
- Molten salt tanks are heated by concentrated solar heat reaching a temperature of above 500ºC
- Water runs through the molten salt tanks in which it is boiled and superheated
- The resulting steam is directed to turbines to produce power
- Steam leaving the turbine is condensed and pumped back to the molten salt tanks to repeat the heat engine cycle
- The plant can store solar heat and use it for a period of 15 hours in the absence of daylight

the net rate of solar radiation supplied to the receiver $\dot{Q}_r = \eta_{ar} A_a G$

η_{ar} : optical efficiency parameter
A_a : solar collector area
G : Incident solar radiation (W/m^2)

$$\dot{Q}_{\text{loss}} = UA_r(T_c - T_a)$$

{ T_c : Average collector temp
T_a : Ambient temperature }

$$\dot{Q}_{\text{useful}} = \dot{Q}_r - \dot{Q}_{\text{loss}} = \eta_{ar} A_a G - UA_r(T_c - T_a)$$

{ U: Loss coefficient, W/m^2K }

$$\eta_c = \frac{\dot{Q}_{\text{useful}}}{\dot{Q}_{\text{incident}}} = \frac{\eta_{ar} A_a G - UA_r(T_c - T_a)}{A_a G}$$
$$= \eta_{ar} - \frac{UA_r(T_c - T_a)}{A_a G} = \eta_{ar} - \frac{U(T_c - T_a)}{\text{CR} \times G}$$

$\left\{ CR = \frac{A_a}{A_r} \right\}$

Advantages

- Higher thermodynamic efficiency can be achieved
- Possible to achieve a thermodynamic match between temperature level and task
- The thermal efficiency is greater because of the small heat loss area relative to the receiver area
- Reflecting surfaces require less material and are structurally simpler than flat-plate collectors

  (For a concentrating collector, the cost per unit area of the solar-collecting surface is therefore less than that of a flat plate collector)
- Selective surface treatment and vacuum insulation to reduce heat losses and improve the collector efficiency are economically viable

Limitations

- Concentrator systems collect little diffuse radiation, depending on the concentration ratio
- Some form of tracking system is required to enable the collector to follow the sun
- Solar reflecting surfaces may lose their reflectance with time and may require periodic cleaning and refurbishing

Solar Tracking

- A tracking mechanism must be reliable and able to follow the sun with a certain degree of accuracy, return the collector to its original position at the end of the day or during the night, and track during periods of intermittent cloud cover
- They can be divided into two broad categories: mechanical and electrical-electronic systems
  - Mechanisms employing motors controlled electronically through sensors, which detect the magnitude of the solar illumination
  - Mechanisms using computer-controlled motors, with feedback control provided from sensors measuring the solar flux on the receiver

Solar Chimney Power Plant

Factors Affecting Technical and Economic Viability

- Amount of annual sunshine/solar resource
- Capital cost of the solar system
- Prices of conventional fuels
- Solar system annual O&M cost
- Annual energy requirement and energy use profile
- Rate at which conventional fuels are escalating in price
- Other (legislative requirements, tax benefits etc.)