Fuel and Energy

Solar Thermal Systems

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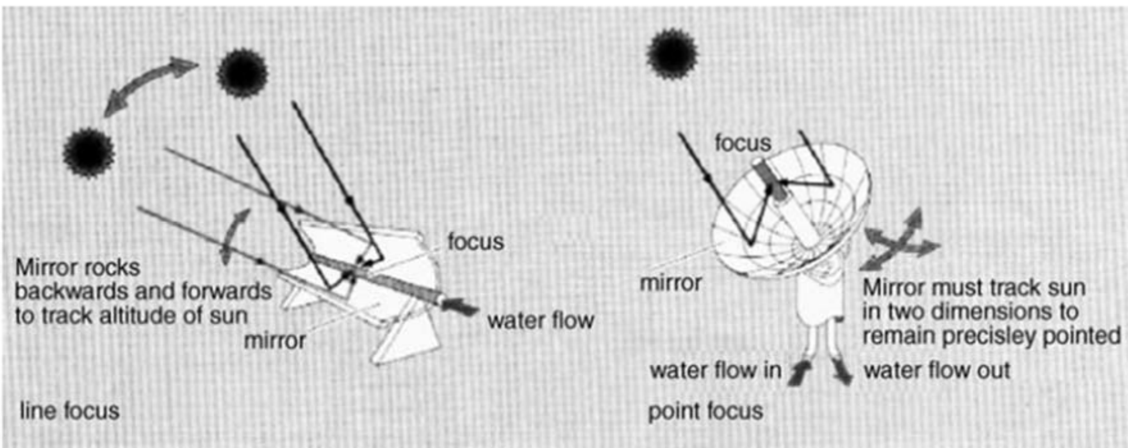
Introduction

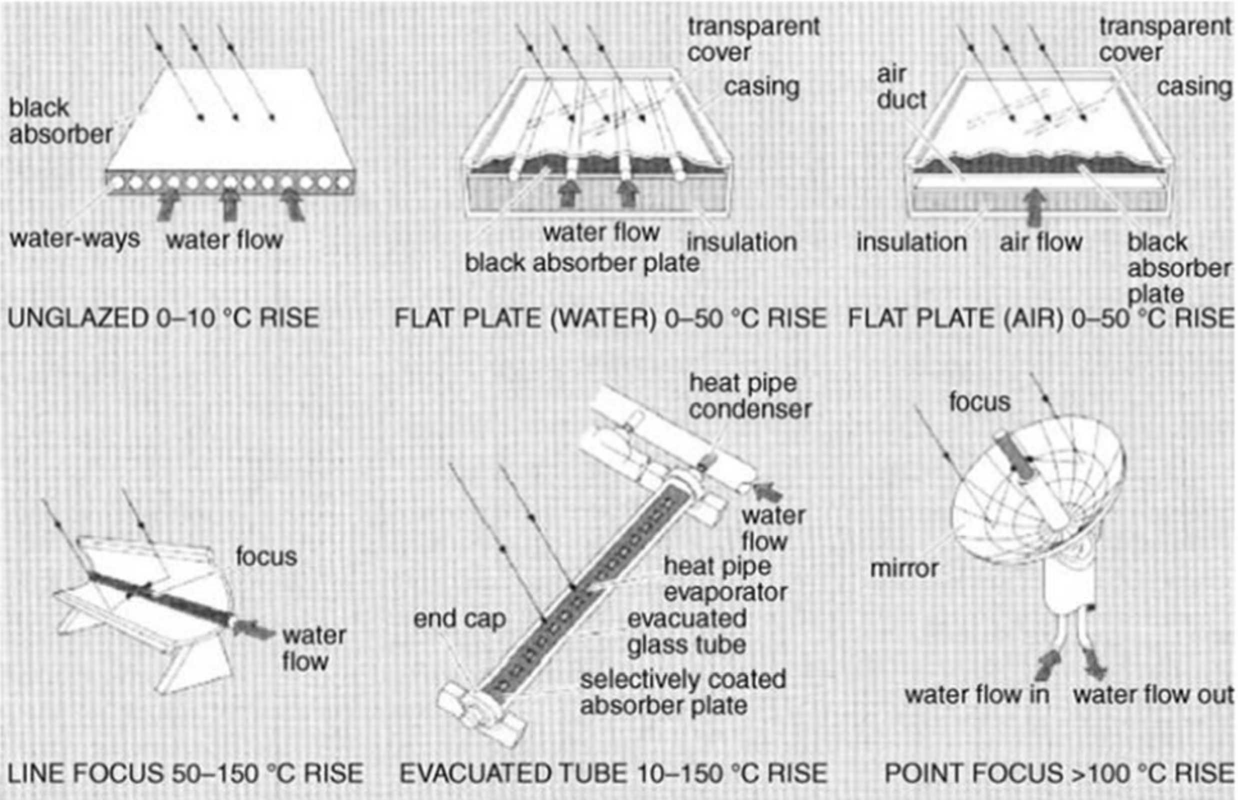
- The solar thermal power system collects the thermal energy in solar radiation and uses it at high or low temperatures.
- Low-temperature applications include water and room heating for commercial and residential buildings.
- High-temperature applications concentrate the sun's heat energy to produce steam for driving electrical generators.
- Concentrating solar power (CSP) technology has the ability to store thermal energy from sunlight and deliver electric power during dark or peak-demand periods.
- For solar energy systems, if the insolation is absorbed and utilized without significant mechanical pumping and blowing, the solar system is said to be **passive**.
- If the solar heat is collected in a fluid, usually water or air, which is then moved by pumps or fans for use, the solar system is said to be **active**.

Solar Collectors

- Solar collectors are distinguished as low-, medium-, or high-temperature heat exchangers.
- There are basically three types of thermal solar collectors: flat plate, evacuated tube, and concentrating.
- Their purpose remains the same: to convert the solar radiation into heat to satisfy some energy needs.
- The heat produced by solar collectors can supply energy demand directly or be stored.



Solar Collectors



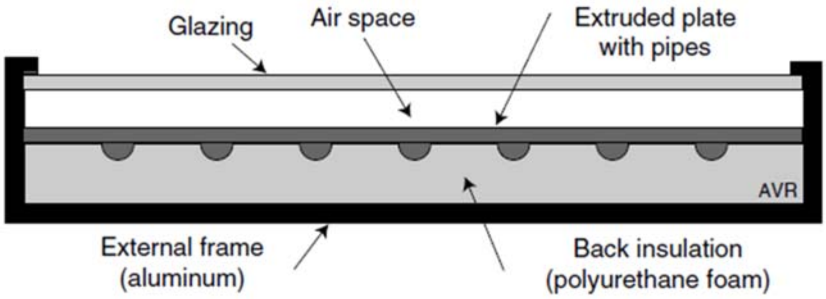
Solar Collectors

Solar Thermal Collectors

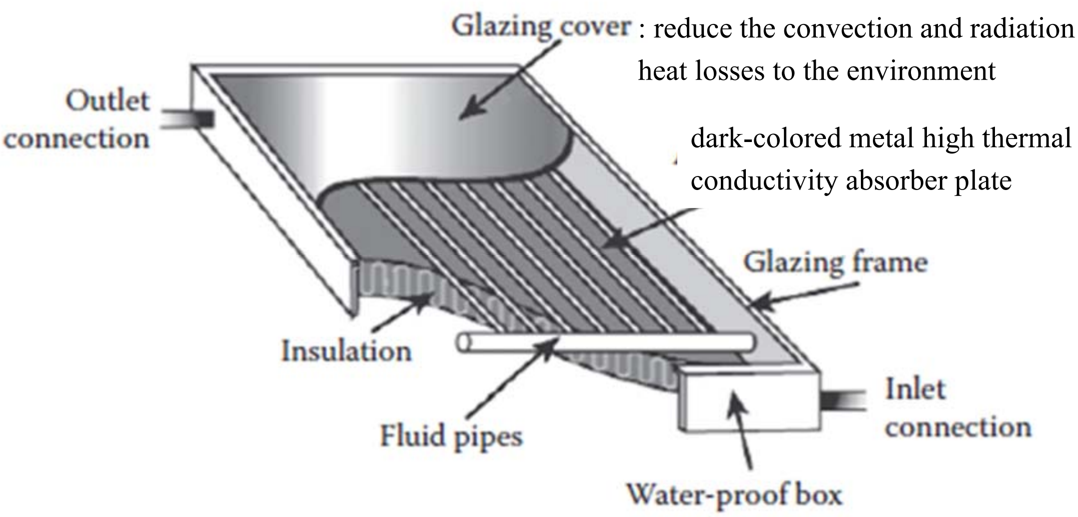
Collector type	Temperature range (°C)	Concentration ratio
Flat-plate collector	30–80	1
Evacuated-tube collector	50–200	1
Compound parabolic collector	60–240	1–5
Fresnel lens collector	60–300	10–40
Parabolic trough collector	60–250	15–45
Cylindrical trough collector	60–300	10–50
Parabolic dish reflector	100–500	100–1,000
Heliostat field collector	150–2,000	100–1,500

Flat-Plate Collectors

- Flat collectors work with both direct and diffused light.
- They provide low temperature heat (less than 70 °C) useful for ambient heating, domestic hot water systems, and swimming pools.
- This type of collector is affected by weather, and its efficiency decreases if large temperature rises are demanded.
- For η > 90 %, it is necessary to operate them so that large volumes of water are only slightly heated rather than heating small amounts of water to a high temperature



Flat-Plate Collectors



(metal or fiberglass insulated box)

Flat-Plate Collectors

➢ The instantaneous energy gained by the receiver

$$\dot{Q}_r = \dot{q}_r A_c = (\tau\alpha)_{eff} I_T A_c$$

τ: the transmittance of the glazing

α: absorbtivity of the blackened-metal receiver

$(\tau\alpha)_{eff}$ is the effective optical fraction of the energy absorbed,

I_T is the solar radiation incident on the tilted collector, OR G

A_c is the collector aperture area.

➢ Solar collectors present great heat losses due to the temperature difference between the absorber plate and the ambient causes heat losses by convection to the surroundings according to

$$\dot{Q}_{conv} = \dot{q}_{conv} A_r = UA_r(T_r - T_a)$$

$$U_L = 1/(R_L A_r)$$

Flat-Plate Collectors

where A_r is the area of the receiver,

U is an overall heat loss coefficient,

T_r is the receiver's temperature

T_a is the ambient temperature.

R_L is the resistance to heat loss from the plate (temperature T_r) to the outside environment (temperature T_a)

➢ Some heat is lost by radiation due to the difference of temperature between the collector and the sky dome

$$\dot{Q}_{rad} = \dot{q}_{rad} A_r = \varepsilon_{eff} \sigma A_r (T_r^4 - T_a^4)$$

where ε_{eff} is the effective emissivity of the collector and σ is the Stefan–Boltzmann constant.

➢ The usable energy collected is obtained from the energy balance on the collector

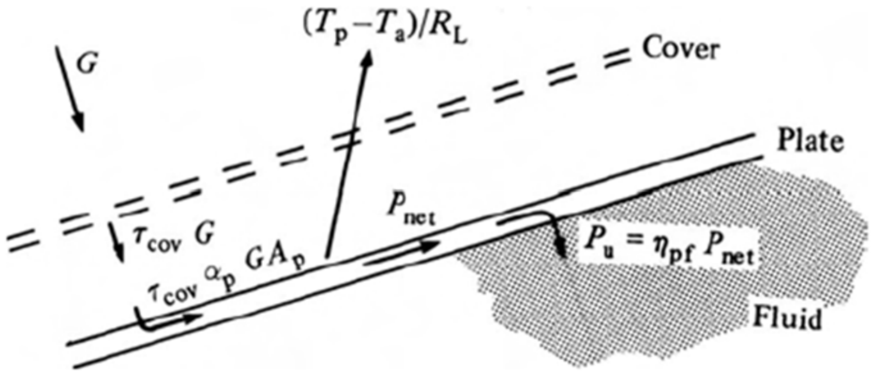
$$\dot{Q}_u(t) = \dot{q}_u A_c = (\tau\alpha)_{eff} I_T A_c - UA_r(T_r - T_a) - \varepsilon_{eff}\sigma A_r(T_r^4 - T_a^4) \quad = \eta_{sp} A_c I_T$$

where $\dot{Q}_u$ is the usable energy collected. η_{sp} is the capture efficiency (<1)

Flat-Plate Collectors

- A heat-conducting fluid, usually water, glycol, or air, passes through pipes attached to the absorber plate. As the fluid flows through the pipes, its temperature increases.
- This is the energy to be utilized for productive activities (e.g., power generation).
- The amount of the energy taken by the working fluid corresponds to a fraction of the useful energy collected after the heat losses, η_{pf} (transfer efficiency)

Typically $\eta_{pf} = 0.85$ and is almost independent of the operating conditions,



Flat-Plate Collectors

- The instantaneous thermal efficiency corresponds to the fraction from the incoming solar radiation

$$\eta_c = \eta_{pf}\frac{\dot{Q}_u}{I_T A_c} = \left[(\tau\alpha)_{eff} - \frac{UA_r}{I_T A_c}(T_r - T_a) - \frac{\varepsilon_{eff}\sigma A_r}{I_T A_c}(T_r^4 - T_a^4)\right]\eta_{pf}$$

- For low-temperature collectors such as flat plate, heat losses by radiation are very small compared to convection losses

$$\eta_c = \eta_{pf}\frac{\dot{Q}_u}{I_T A_c} = \left[(\tau\alpha)_{eff} - \frac{UA_r}{I_T A_c}(T_r - T_a)\right]\eta_{pf}$$

the collector efficiency η_c is the product of the capture efficiency η_{sp} and the transfer efficiency η_{pf}:

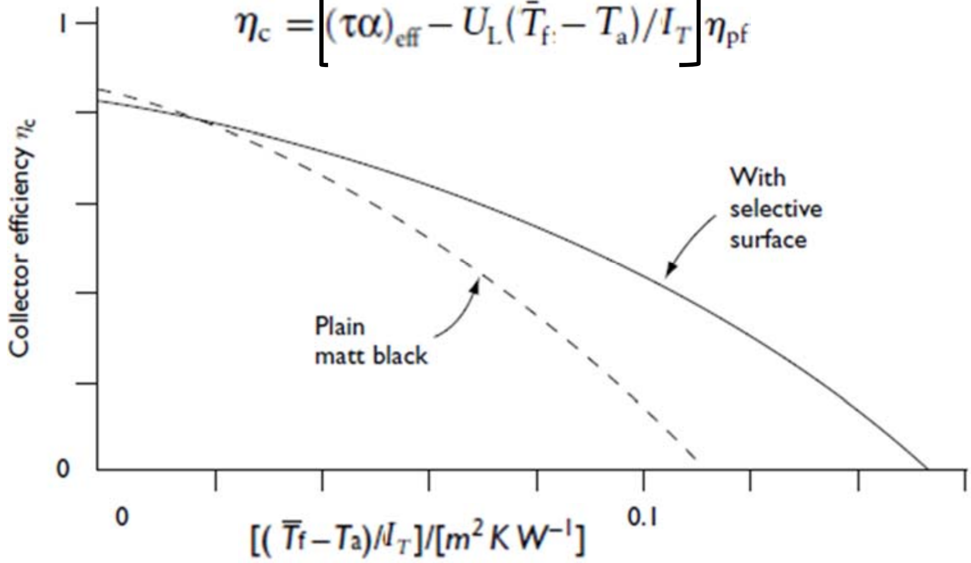
$$\eta_c = \eta_{sp}\eta_{pf}$$

$$\eta_{sp} = (\tau\alpha)_{eff} - U_L(T_r - T_a)/I_T$$

Flat-Plate Collectors

- As the plate temperature T_r in an operating collector is not usually known, it is more convenient to relate the useful energy gain to the mean fluid temperature $\bar{T}_f$,

$$\eta_c = \left[(\tau\alpha)_{eff} - U_L(\bar{T}_f - T_a)/I_T\right]\eta_{pf}$$



Typical efficiency curves of single-glazed flat plate collectors. $\bar{T}_f$ is the mean temperature of the working fluid and T_a is ambient temperature.

Flat-Plate Collectors

- The usable heat gained by the working fluid is

$$\eta_{pf}\,\dot{Q}_u = \dot{m}C_p\left(T_{out} - T_{in}\right)$$

where T_{out}, C_p, and $\dot{m}$ are the fluid outlet temperature, heat capacity at constant pressure, and mass flow rate of the working fluid, respectively.

Flat plate efficiencies

- Two-pane design only transmits about 85% of incident light, due to surface reflections
- Collector is not a *perfect* absorber, and maybe bags 95% of incident light (guess)
- Radiative losses total maybe 1/3 of incident power
- Convective/Conductive losses are another 5–10%
- Bottom line is approximately 50% efficiency at converting incident solar energy into stored heat
  - $0.85 \times 0.95 \times 0.67 \times 0.90 = 0.49$

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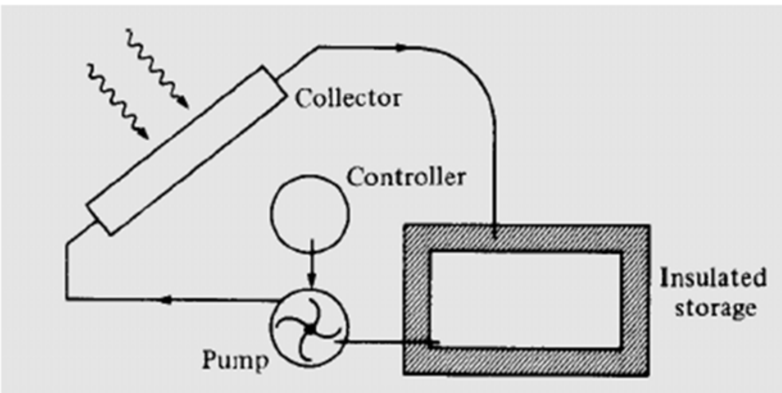
Example

A flat plate collector measuring $2\,\mathrm{m} \times 0.8\,\mathrm{m}$ has a loss resistance $r_L = 0.13\,\mathrm{m^2\,K\,W^{-1}}$ and a plate transfer efficiency $\eta_{pf} = 0.85$. The glass cover has transmittance $\tau = 0.9$ and the absorptance of the plate is $\alpha = 0.9$. Water enters at a temperature $T_1 = 40\,°\mathrm{C}$. The ambient temperature is $T_a = 20\,°\mathrm{C}$ and the irradiance in the plane of the collector is $G = 750\,\mathrm{W\,m^{-2}}$.



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Example cont.

a Calculate the flow rate needed to produce a temperature rise of 4 °C.

$$q_u = (\rho c Q/A)(T_2 - T_1) = \eta_{pf}[\tau\alpha G - (T_p - T_a)/r_L]$$

Assuming $T_p = 42\,°C$ (the mean temperature of the fluid), this yields

$$Q = 3.5 \times 10^{-5}\,m^3\,s^{-1} = 130\,L\,h^{-1}$$

How much would a household need?

- Typical showers are about 10 minutes at 2 gallons per minute, or 20 gallons.
- Assume four showers, and increase by 50% for other uses (laundry) and storage inefficiencies:
  - 20×4×1.5 = 120 gallons ≈ 450 liters
- To heat 450 *l* from 15 ºC to 50 ºC requires:

  (4184 J/kg/ºC)×(450 kg)×(35 ºC) = 66 MJ of energy
- Over 24-hour day, this *averages* to 762 W
- At average insolation of 200 W/m^2 at 50% efficiency, this requires 7.6 m^2 of collection area
  - about 9-feet by 9-feet, costing perhaps $6–8,000

Evacuated Collectors

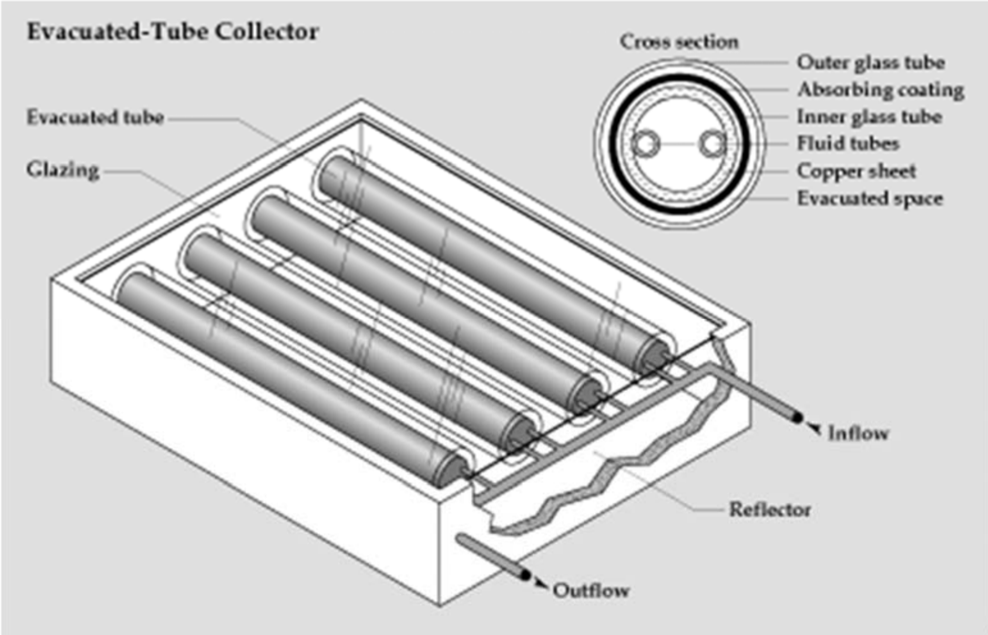
- Evacuated-tube solar collectors have better performance than flat plate for high-temperature operation in the range of 77–170°C.
- They are well suited to commercial and industrial heating applications and also for cooling applications by regenerating refrigeration cycles.
- They can also be an effective alternative to flat-plate collectors for domestic space heating, especially in regions where it is often cloudy.
- An evacuated-tube solar collector consists of rows of parallel glass tubes connected to a header pipe.
- The air within each tube is removed reaching vacuum pressures around 10–3 mbar to eliminate heat loss through convection and radiation.
- This creates high insulation conditions to eliminate heat loss through convection and radiation, for which higher temperatures than those for flat-plate collectors can be attained.
- A variant to the vacuum is that the tube can use a low thermal conductivity gas such as xenon.

Evacuated Collectors

- Evacuated-tube solar collector are classified according to:
    - Their connecting-material joints as glass–metal or glass–glass and,
    - The arrangement of the tubes (such as concentric or U-pipe).
- Inside each evacuated tube, a flat or curved metallic fin is attached to a copper or glass absorber pipe.
- The fin is coated with a selective thin film whose optical properties allow high absorbance of solar radiation and impede radiative heat loss.
- The glass–metal collector type is very efficient, although it can experience loss of vacuum due to the junction of materials with very different heat expansion coefficients

Direct-flow evacuated-tube collectors

➢ The heat transfer fluid is water and circulates through the pipes, one for inlet fluid and the other for outlet fluid



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Heat pipe evacuated-tube collectors

➢ These consist of a metal (copper) heat pipe, to which is attached a black copper absorber plate, inside a vacuum-sealed solar tube.

➢ The heat pipe is hollow and the space inside, like that of the solar tube, is evacuated.

➢ Inside the heat pipe is a small quantity of liquid, such as alcohol or purified water plus special additives.

➢ The vacuum enables the liquid to boil (i.e. turn from liquid to vapor) at a much lower temperature than it would at normal atmospheric pressure.

➢ When solar radiation falls the surface of the absorber, the liquid within the heat tube quickly turns to hot vapor rises to the top of the pipe.

➢ Water, or glycol, flows through a manifold and picks up the heat, while the fluid in the heat pipe condenses and flows back down the tube for the process to be repeated.

➢ An advantage of heat pipes over direct-flow evacuated-tubes is the "dry" connection between the absorber and the header, which makes installation easier and also means that individual tubes can be exchanged without emptying the entire system of its fluid.

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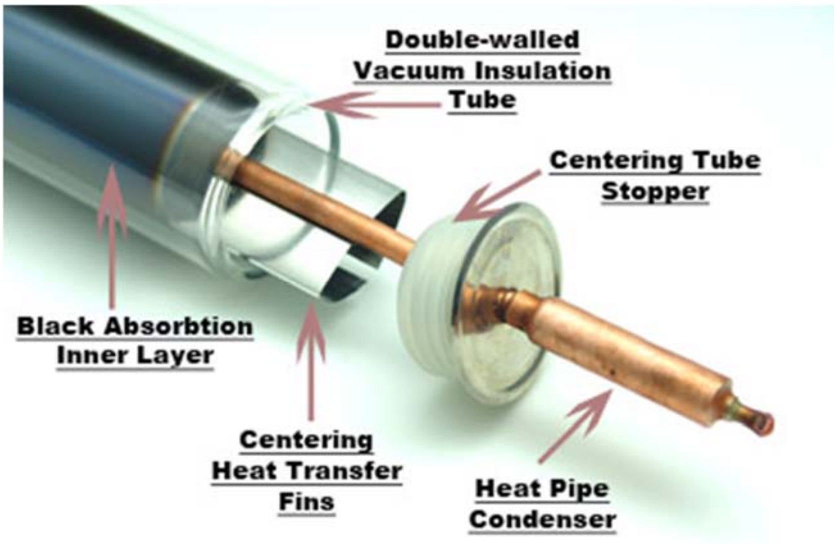
Heat pipe evacuated-tube collectors



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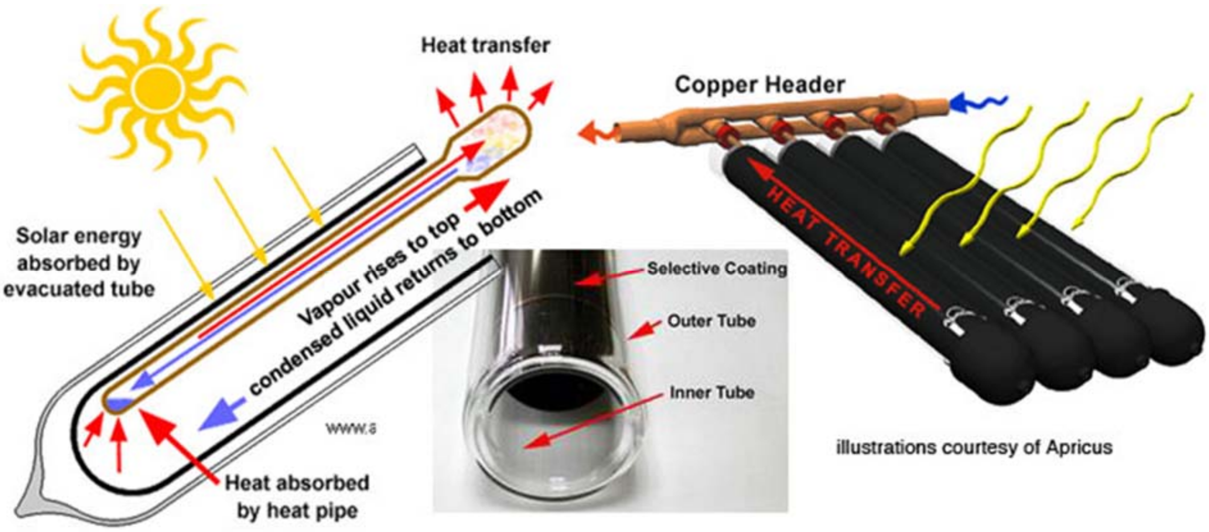

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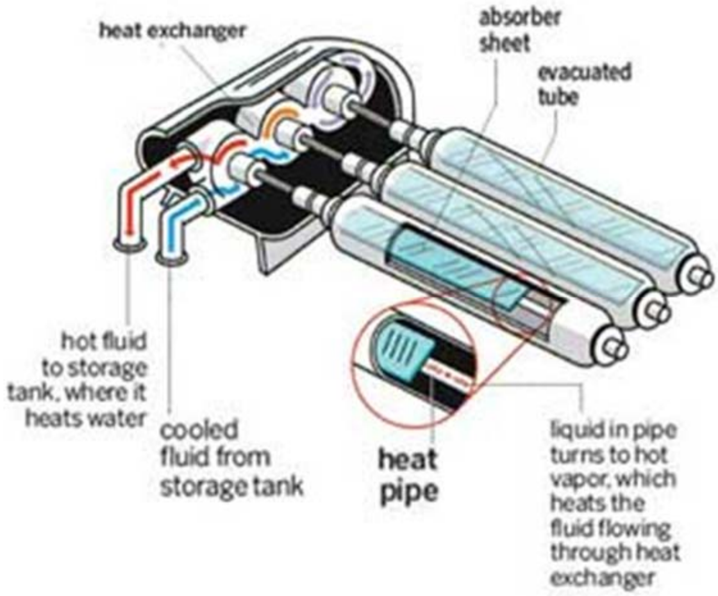

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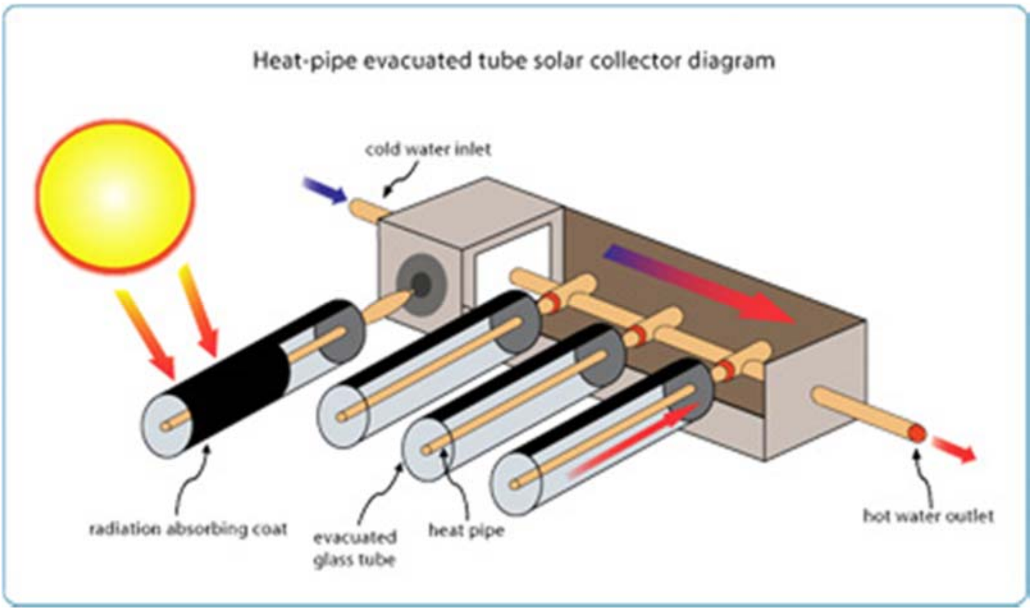
Heat pipe evacuated-tube collectors



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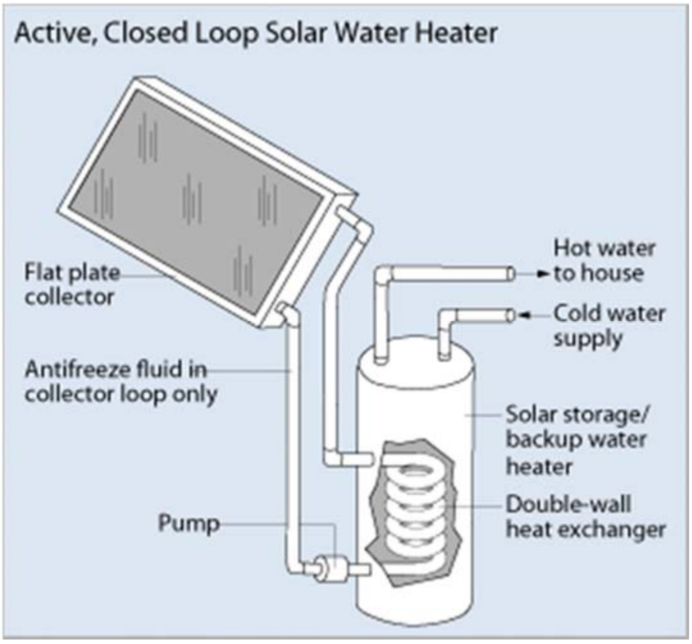
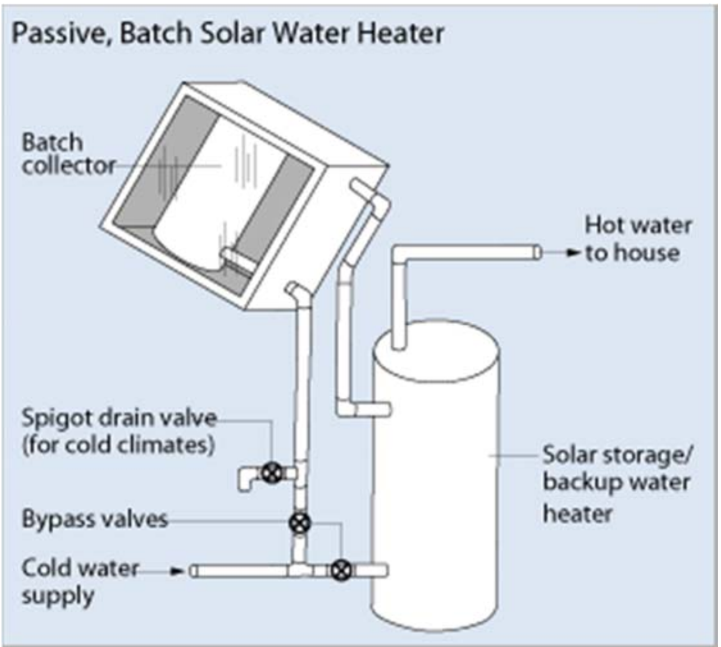
Solar Thermal System



Solar Thermal System



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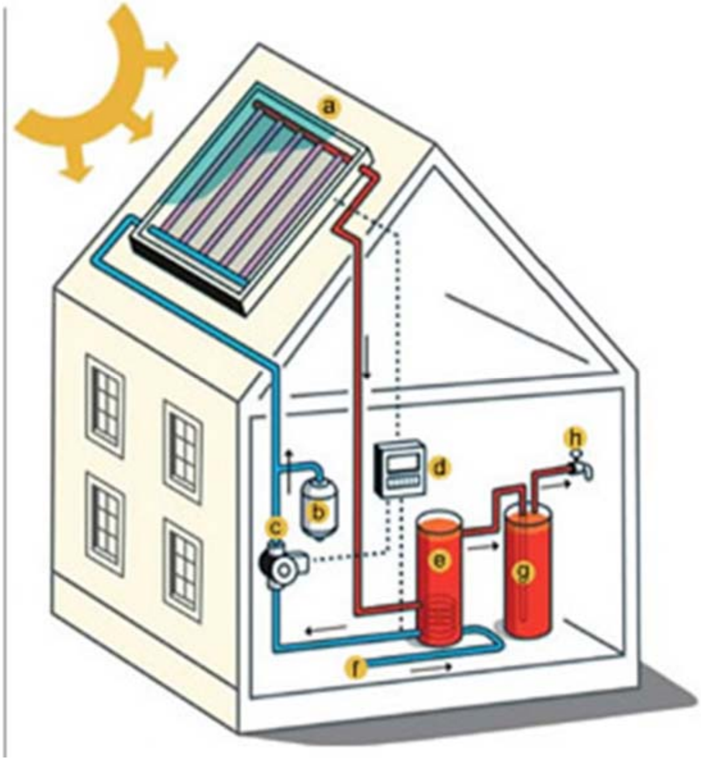

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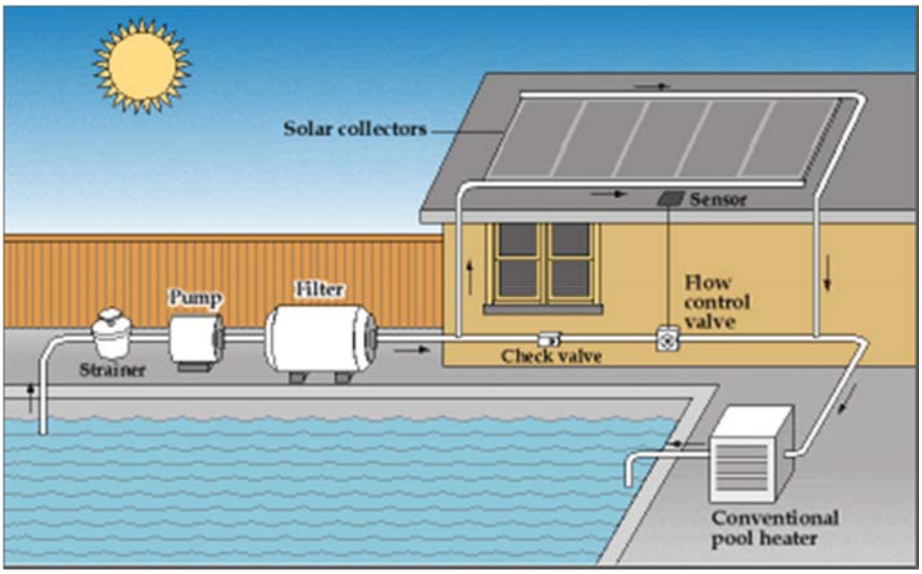
Solar Thermal System



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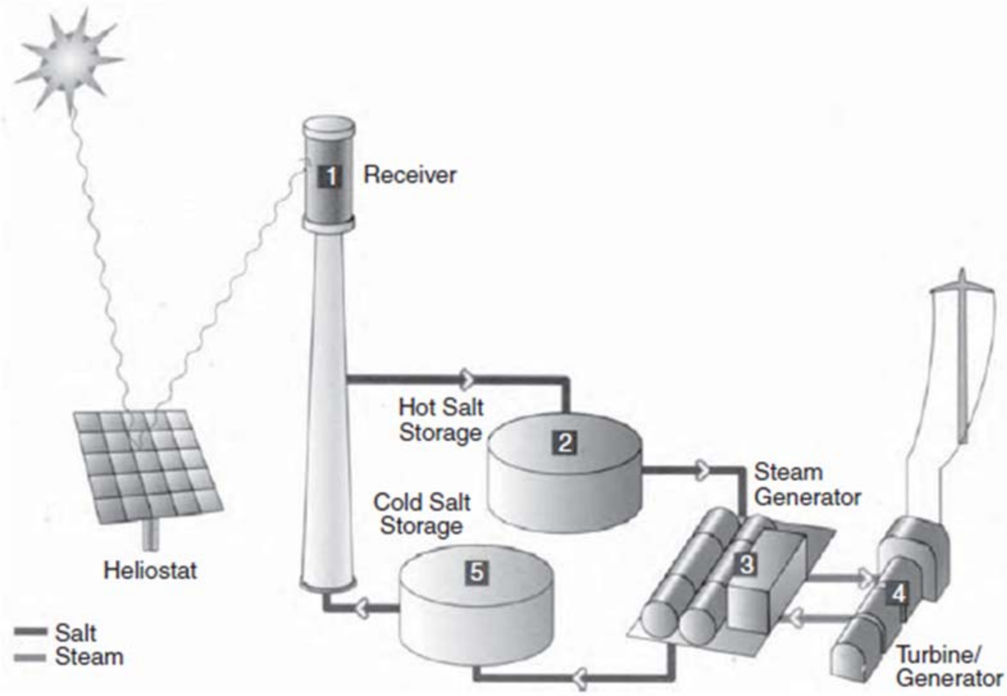
Solar Thermal Power Plant



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Solar power Plant

Power tower in Barstow, California.

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Solar power Plant

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