Lecture 5 – Solar Thermal Energy

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ECE180J

Outline

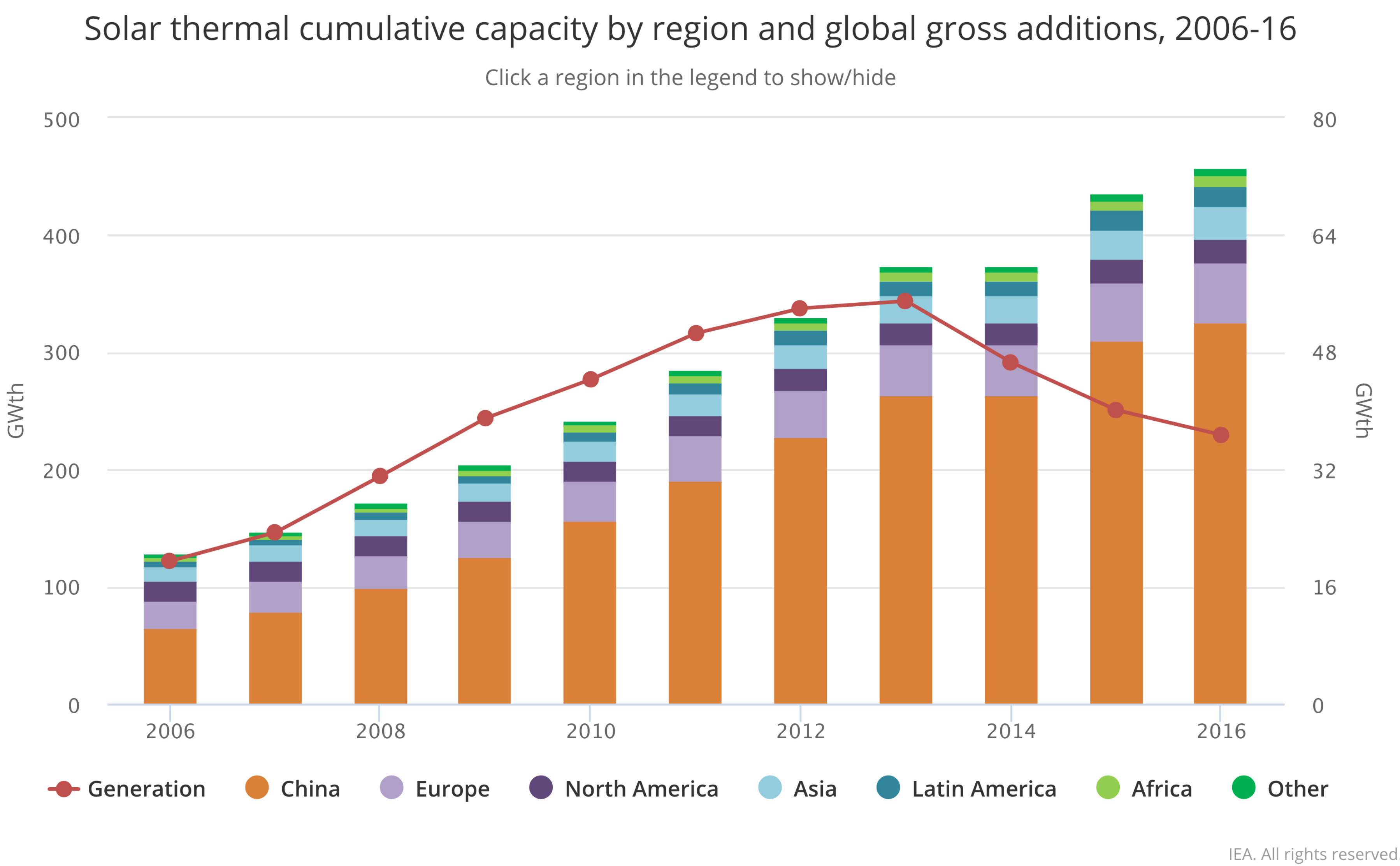
- Heat Transfer Mechanisms
- Passive Solar Heating
- Active Solar Heating

- B3 Chap 3; B1 Chap 4, 8.1-8.2
- Abdul Hai Alami etc, “Concentrating solar power (CSP) technologies: Status and analysis,” International Journal of Thermofluids, Volume 18, 2023.

Solar Thermal Energy

- Solar thermal energy is a form of energy and a technology for harnessing solar energy to generate thermal/electrical energy.
- Solar thermal technologies can produce heat for hot water, space heating and industrial processes, with systems ranging from small residential scale to very large community and industrial scale.
- The required temperature to meet the heat demand determines the collector type and design.

Growth in Solar Thermal Installed Capacity



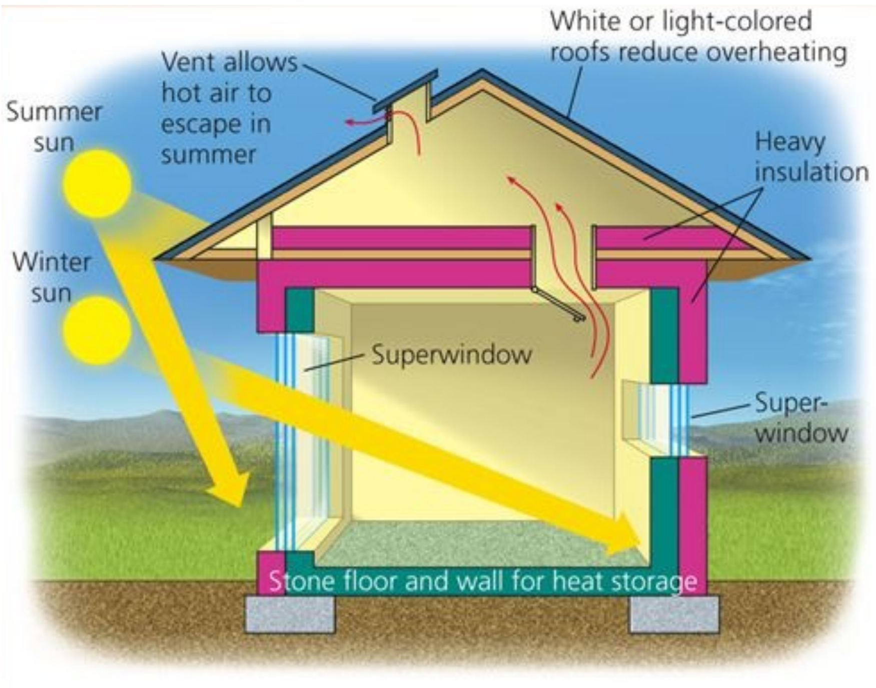
Active vs Passive Heating

Source: www.smarttouchenergy.com/resources/guide-to-home-heating-systems/energy-from-the-sun

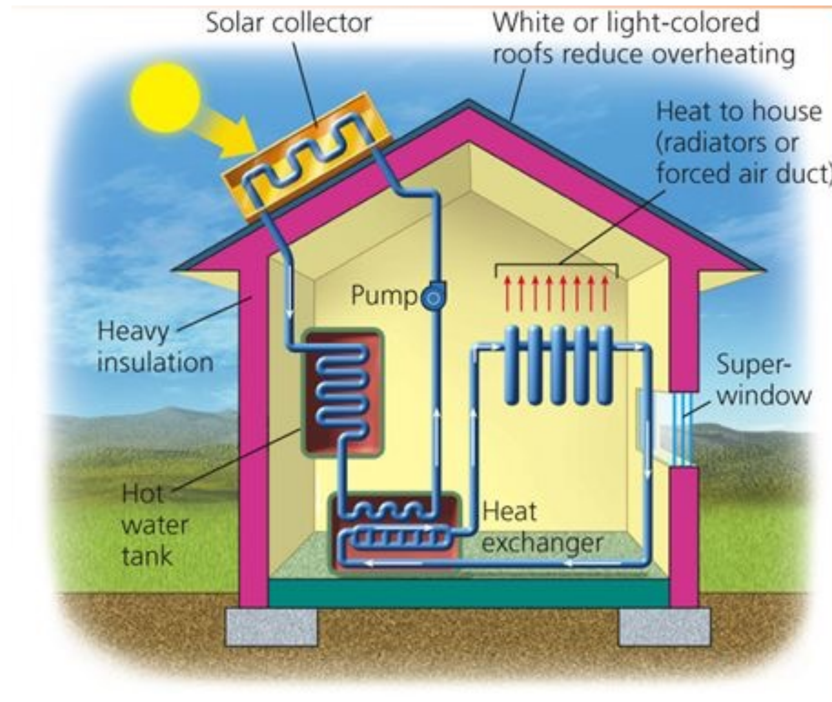
Active vs Passive Heating (cont'd)

Passive solar heating:
absorb solar energy directly into a building

Active solar heating:
involves a discrete solar collector to gather solar radiation



PASSIVE

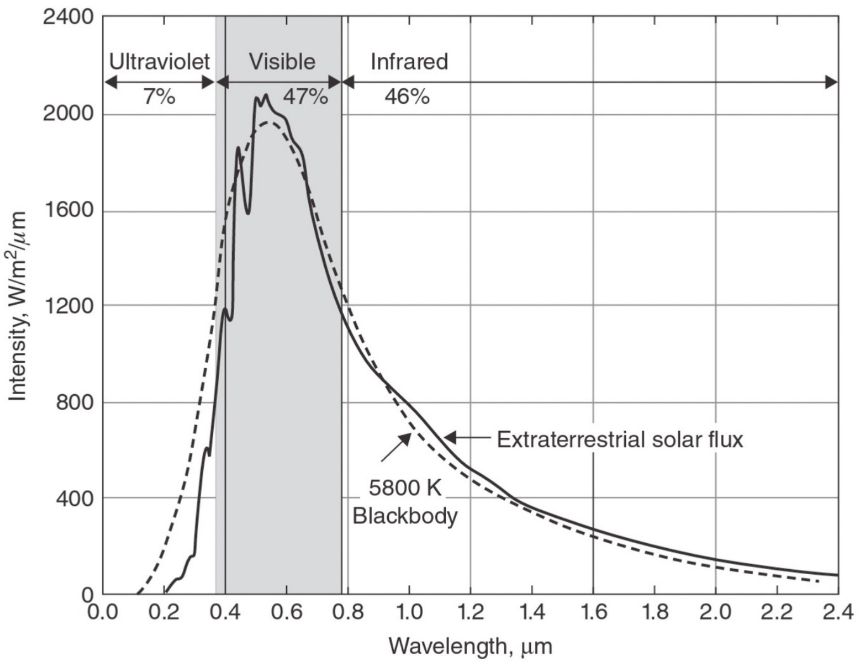


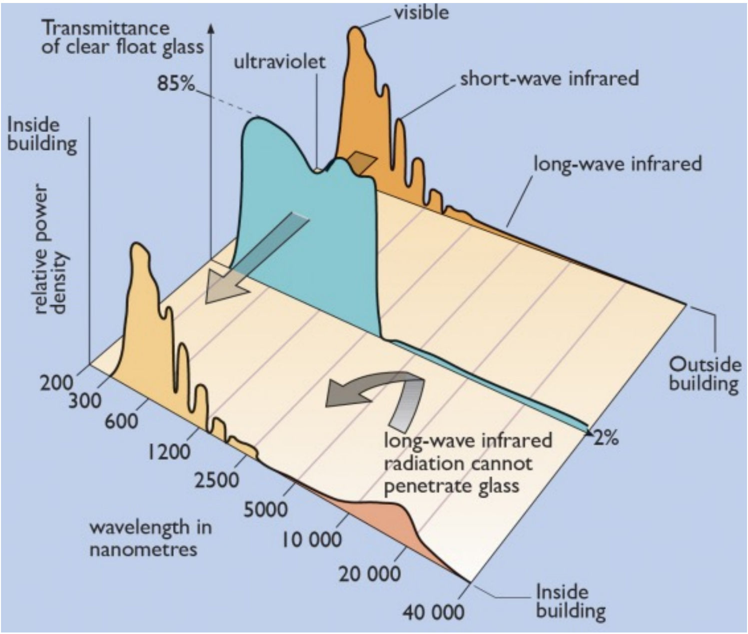
ACTIVE

Cold air is denser than warm air. The molecules are packed closer together. The more water vapor that is in the air, the less dense the air becomes. Cold, dry air is much heavier than warm, humid air.

Passive Solar Heating

Glass as Filter





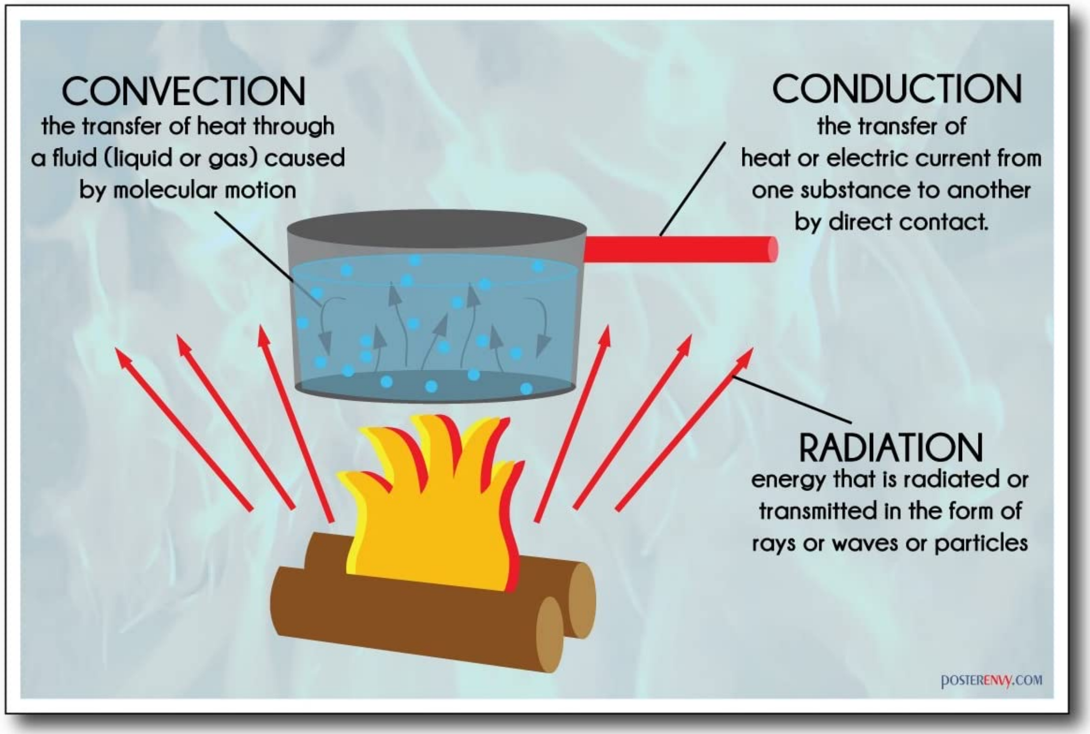
Most low-temperature solar collection is dependent on the properties of **glass:**

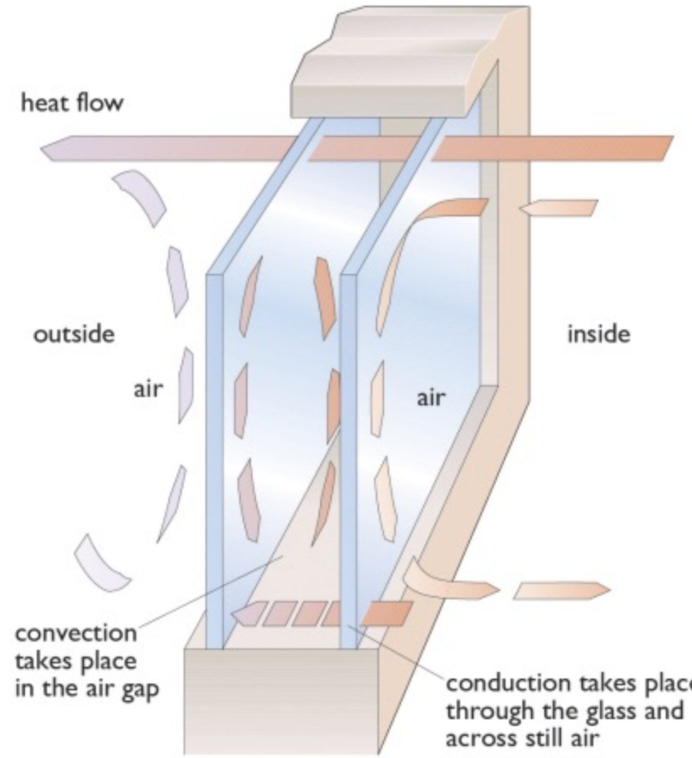
- Transparent to visible light & short-wave infrared radiation
- Opaque to long-wave infrared

Make glass transparent → maximize its transmittance *(fraction of incident light passing through it)* → minimize the iron content of the glass

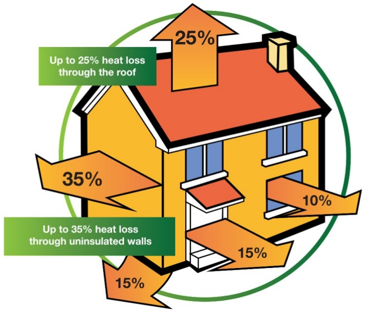
Heat Loss Mechanisms

Heat always flows from a region of higher temperature to a region of lower temperature. It flows by conduction, convection, and radiation.





Heat Flow Rate Equation

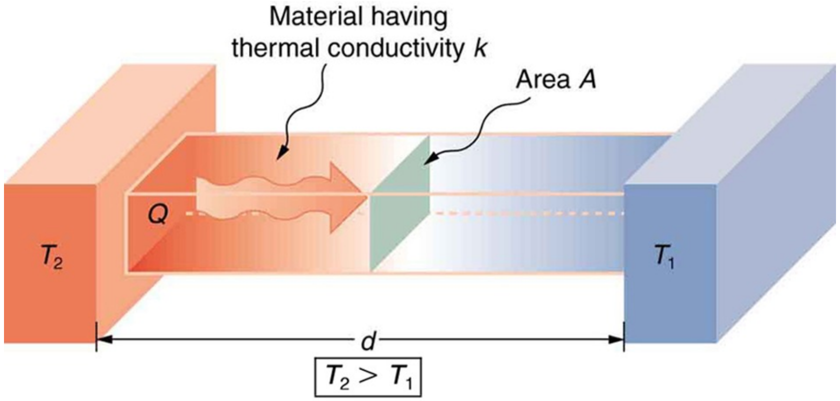


We're interested in regulating the rate at which the thermal energy is transferred. For example:

- keep an object at a temperature different from that of its surrounding for a long time by slowing down heat flow.
- want an object to cool down rapidly by increasing the rate at which thermal energy is transferred.

Law of heat conduction:

$$\boxed{\frac{\Delta Q}{\Delta t} = -\lambda A \frac{\Delta T}{d}}$$



where $\frac{\Delta Q}{\Delta t}$ is the rate of heat flow, λ is the thermal conductivity A is the surface area, Δ T is the change in temperature d is the thickness of the material

The minus sign indicates that heat flows in the opposite direction of the temperature gradient ($\frac{\Delta T}{d}$), from the high to the low temperature side.

Thermal Conductivity

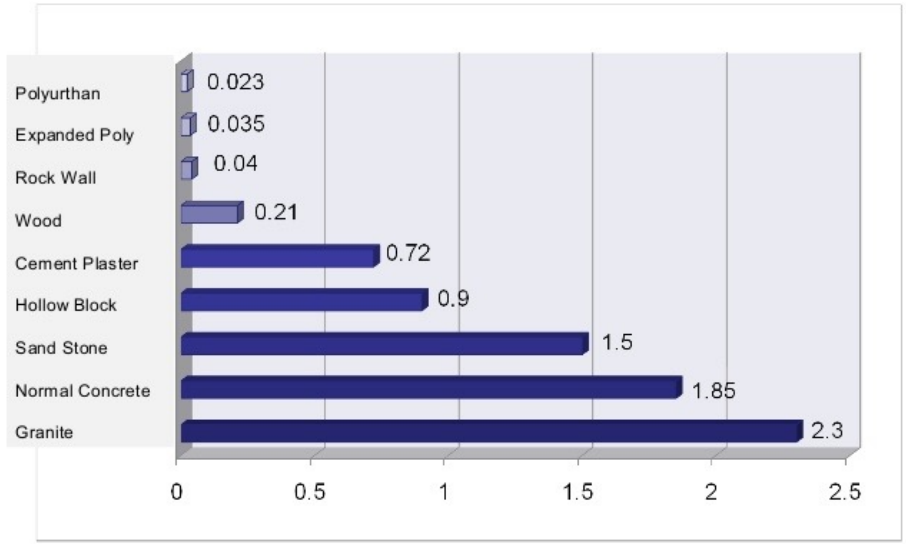
The unit of thermal conductivity factor is: $\text{Watt}/(\text{meter} \times \text{Kelvin})$

Temperature conversions

	from Celsius	to Celsius
Fahrenheit	[°F] = [°C] × $^9/_5$ + 32	[°C] = ([°F] − 32) × $^5/_9$
Kelvin	[K] = [°C] + 273.15	[°C] = [K] − 273.15

Material	Thermal conductivity (W/m K)
Copper (pure)	399
Gold (pure)	317
Aluminum (pure)	237
Iron (pure)	80.2
Carbon steel (1 %)	43
Stainless Steel (18/8)	15.1
Glass	0.81
Plastics	0.2 – 0.3
Wood (shredded/cemented)	0.087
Cork	0.039
Water (liquid)	0.6
Ethylene glycol (liquid)	0.26
Hydrogen (gas)	0.18
Benzene (liquid)	0.159
Air	0.026

Thermal Conductivity Comparison $W/(m.K)$



Example of Heat Flow Equation

Heat flow equation: $$\boxed{\frac{\Delta Q}{\Delta t} = -\lambda A \frac{\Delta T}{d}}$$

Q: Find the rate of heat flow transferred through a 40 cm long aluminum bar with a cross section area of 16 cm^2. The thermal conductivity of the bar is $\lambda = 205\ W/(m \cdot K)$. The temperature at the hot end is 120°F while at the cold end is 20°F.

A: The key is to correctly convert some units.

$$120^{\circ}F = 322.039^{\circ}K$$

$$20^{\circ}F = 266.483^{\circ}K$$

$$\Delta T = 322.039 - 266.483 = 55.56^{\circ}K$$

$$\frac{\Delta Q}{\Delta t} = \lambda A \frac{\Delta T}{d} = 205 \times 16 \times 10^{-4} \times \frac{55.56}{0.4} = 45.56\ W$$

Window U-value and Heat Loss

Heat flow rate per square meter = U-value × temperature difference

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

Source: BRE, 2013

The lower the U-value, the better the insulation performance !

Q: What is the rate of heat loss through a large sing-glazed window with an area of $2m^2$, on a day when indoor-outdoor temperature difference is 15℃? What is the total heat loss on that day?

$$\text{A: Heat loss rate} = 2 \times 4.8 \times 15 = 144 \text{ W} \Rightarrow$$

$$\text{Total heat loss} = 144 \times 24 = 3.456 \text{ kWh}$$

Quiz

Q: What is the rate of heat loss through a large sing-glazed window with an area of 2m^2, on a day when indoor-outdoor temperature difference is 15 ^{0}F? What is the total heat loss on that day?

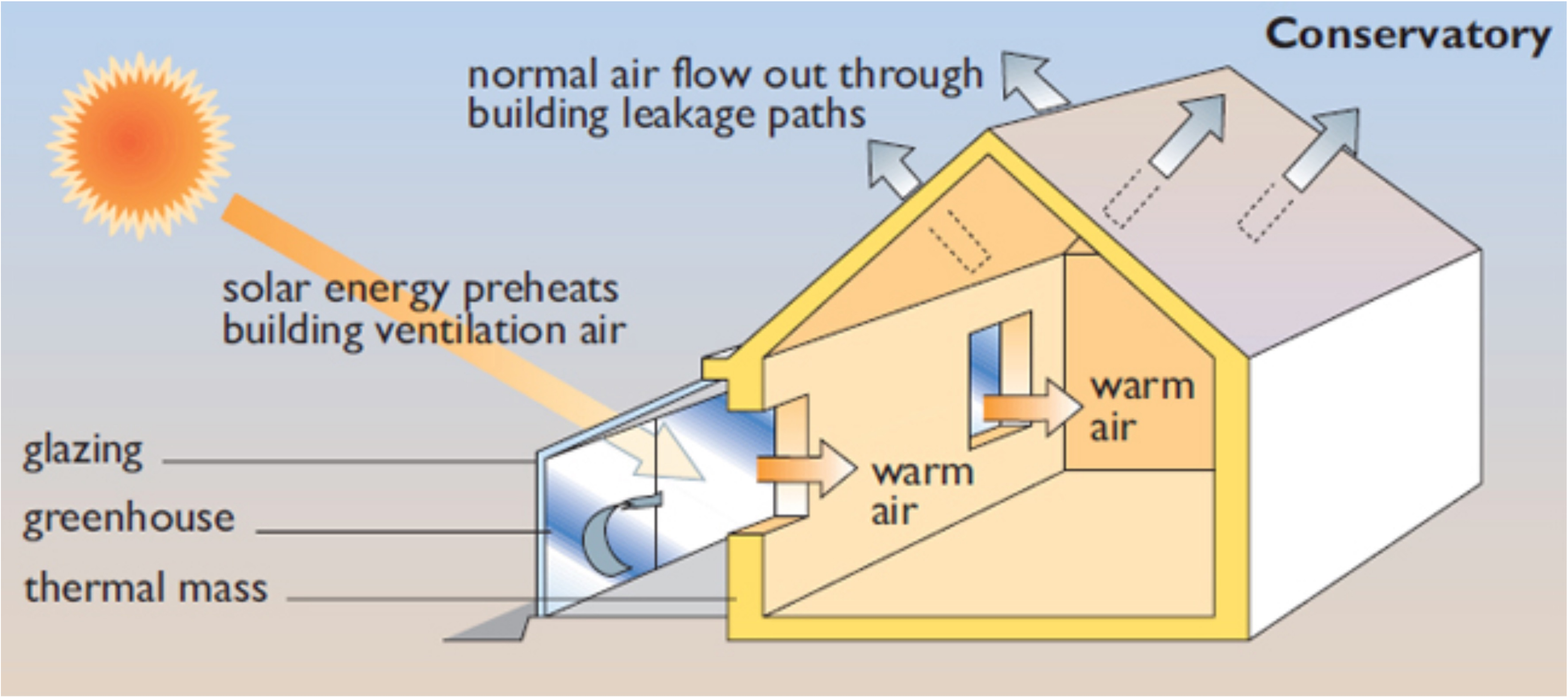
$$\text{A} : [^\circ\text{F}] = [^\circ\text{C}] \times \frac{9}{5} + 32 \Rightarrow \Delta T_{[^\circ\text{F}]} = \Delta T_{[^\circ\text{C}]} \times \frac{9}{5} = \Delta T_{[K]} \times \frac{9}{5}$$

$$\Rightarrow \Delta T_{[K]} = \Delta T_{[^\circ F]} \times \frac{5}{9}$$

$$\text{Heat loss rate} = 2 \times 4.8 \times 15 \times \frac{5}{9} = 80\text{W} \Rightarrow$$

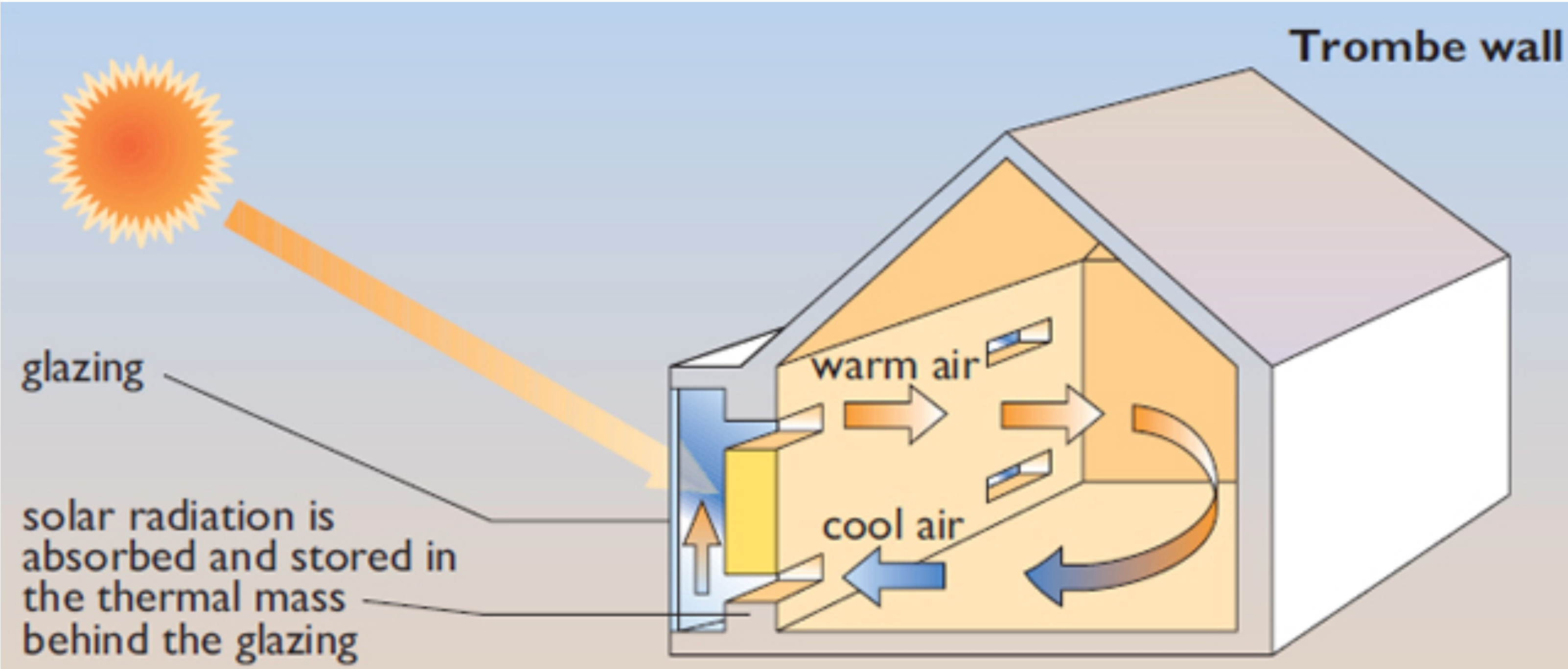
$$\text{Total heat loss} = \text{Heat loss rate} \times \text{time duration} = 80 \times 24 = 1.92\text{kWh}$$

Passive Solar Heating – Conservatory



A conservatory/greenhouse:
The south side of a building can be considered as a kind of habitable solar collector where air is the heat transfer fluid, carrying energy into the building behind, and the energy store is the building itself, especially the wall at the back.

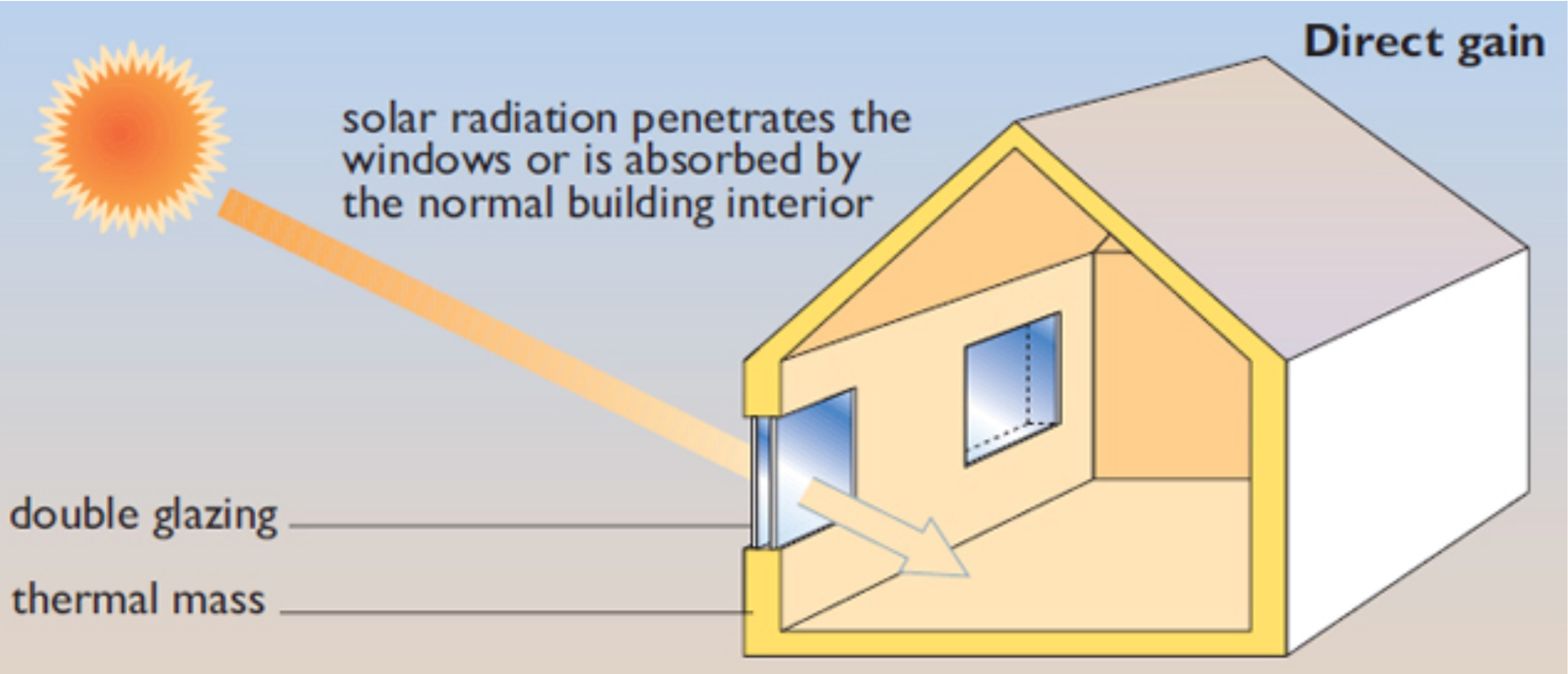
Passive Solar Heating – Trombe Wall



A Trombe wall (named after its French inventor, Félix Trombe):

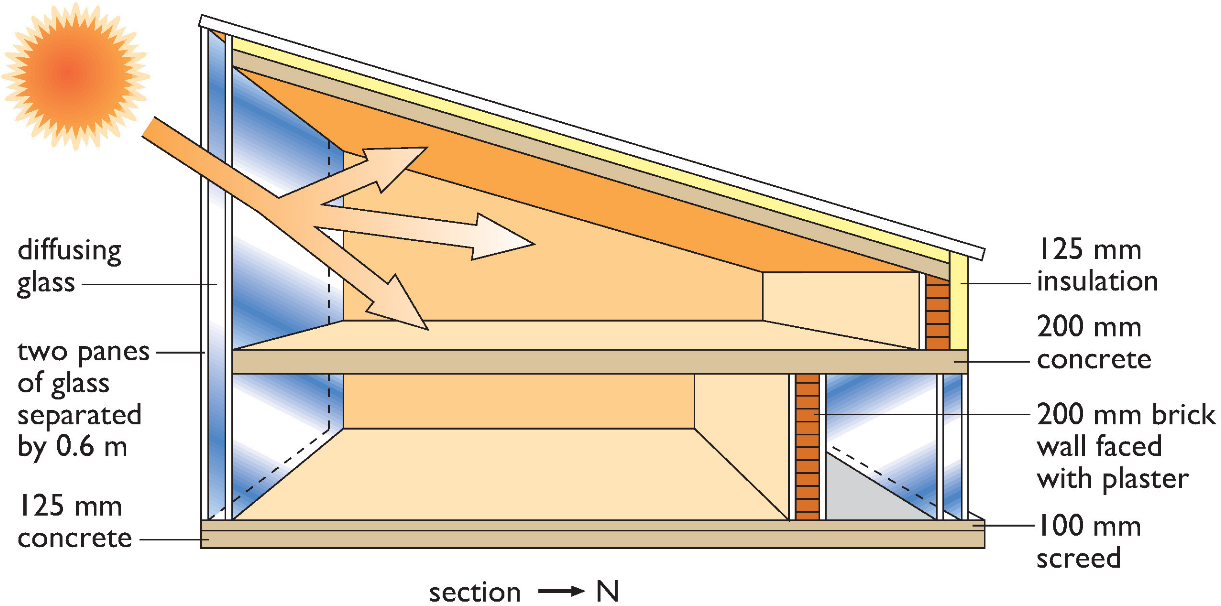
- Conservatory is replaced by a thin glazed air space in front of a storage wall.
- Solar radiation warms the storage wall and is radiated into the house from its inner side.
- On Sunny days air is circulated through vents in the air space into the house behind. At night and on cold days, this air flow is cut off.

Passive Solar Heating – Direct Gain



- All glazed buildings make use of 'direct gains' of energy from the Sun to some degree.
- If the building is 'thermally massive' enough, i.e. built of heavy materials such as concrete, and the heating system is responsive, the solar heat gains are useful.
- If the building is too 'thermally lightweight', such as one of timber frame construction, it may overheat on Sunny days.

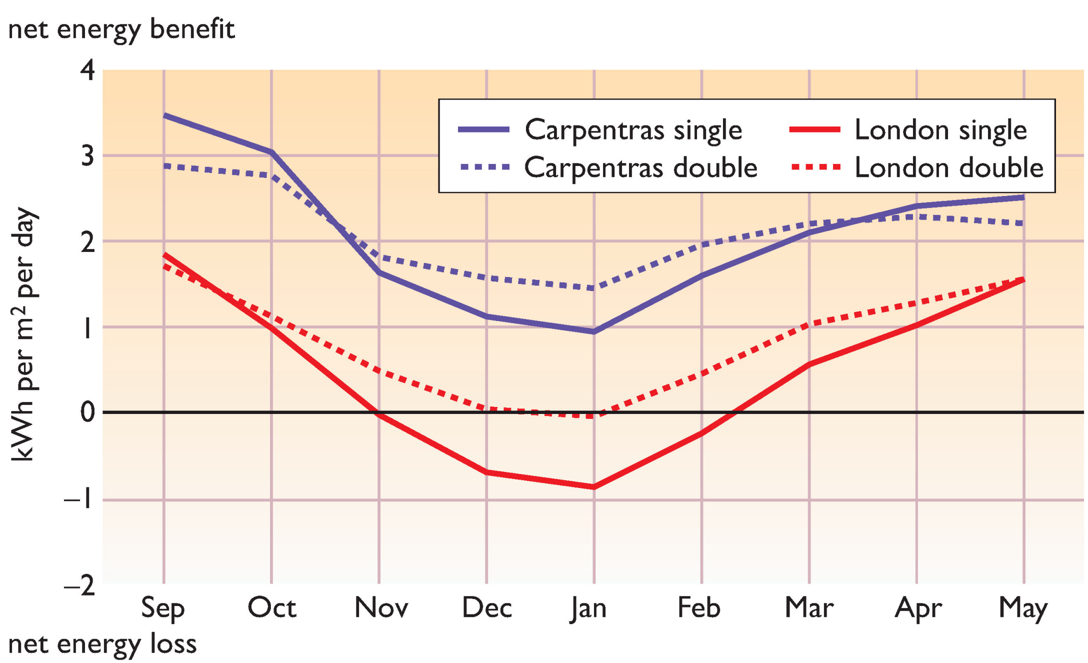
Wallasey Solar Campus

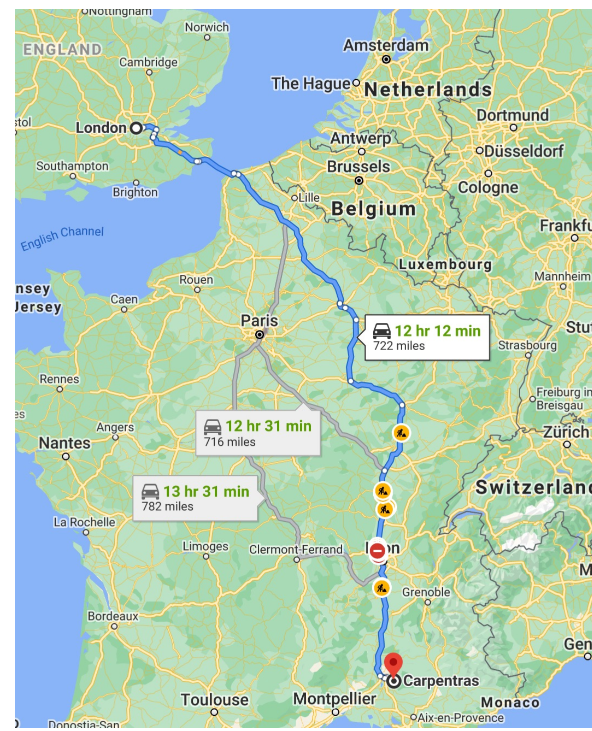


Window Energy Balance

Q: Can a window gets more heat flows in than out so that it provides net energy benefits? What factors shall we consider?

A: Depends on the following factors:
1) average internal and external temperature
2) available solar radiation
3) transmittance, U-value, orientation, and shading of the window





Quiz

Q: What general guidelines can you think of for optimizing the use of passive solar heating in buildings?

Answer:

- Be well-insulated to keep down the overall heat losses
- Have a responsive, efficient heating system
- In the northern hemisphere they should face south (anywhere from south-east to south-west is fine), and the glazing should be concentrated on the south side, as should the main living rooms; little-used rooms (e.g. bathrooms) on the north.
- Be sited to avoid overshading by other buildings in order to benefit from the essential mid-winter sunshine.
- Be ‘thermally massive’ to avoid overheating in summer.

Daylighting

Fig: Modern deep-plan office buildings, such as those at Canary Wharf in London, require continuous artificial lighting in their center, which may create overheating in summer.

Traditional techniques include:

1. 'shallow-plan' design, allowing daylight to penetrate all rooms and corridors light wells in the center of buildings roof lights
2. tall windows, which allow light to penetrate deep inside rooms
3. the use of task lighting directly over workplaces, rather than lighting the whole building interior

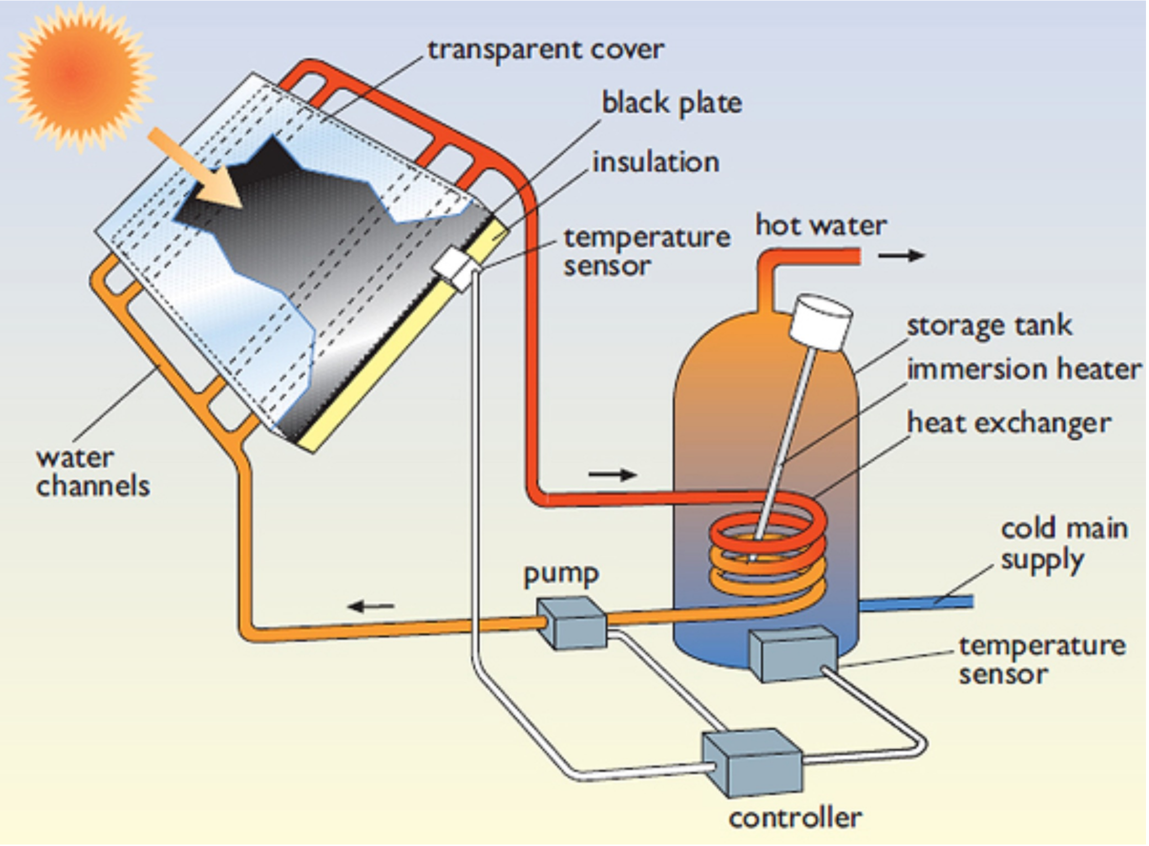
Active Solar Heating

Pumped Solar Water Heater

1. A collector panel, consisting of glazing, an absorber plate, and insulation

2. An insulated hot water storage tank, with hot water from the panel circulating through a heat exchanger situated at the bottom

3. A pumped circulation system containing an anti-freeze transferring the heat from the panel to the store

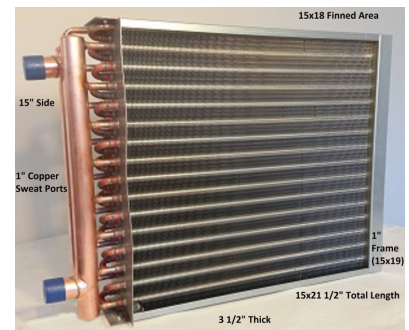


Heater Exchanger

Heater exchanger: A system used to transfer heat between two or more fluids.

- The fluids may be separated by a solid wall to prevent mixing or they may be in direct contact.
- Heat exchangers are widely used in both cooling and heating processes: space heating, refrigeration, air conditioning, power stations, chemical plants, petrochemical plants, petroleum refineries, natural-gas processing, and sewage treatment.

Shell and Tube Heat Exchanger



Water to Air Heat Exchanger

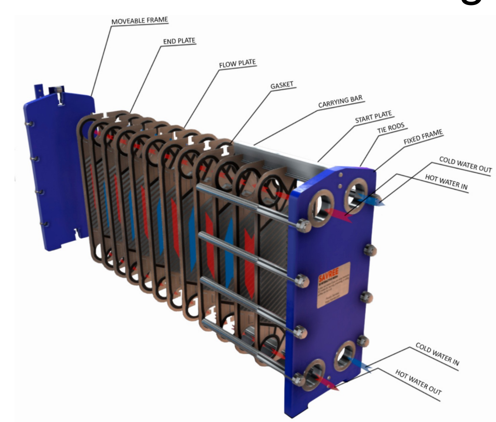
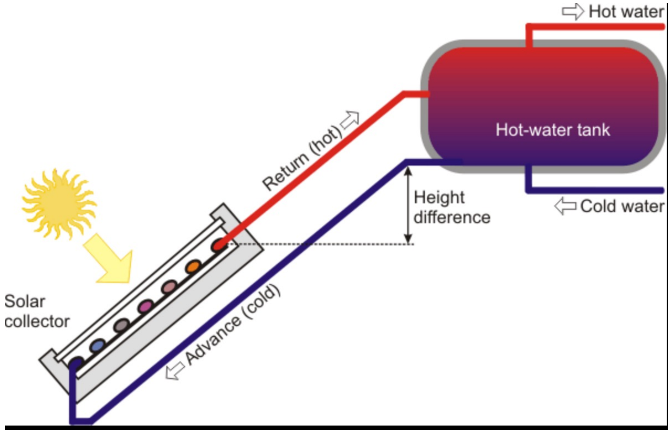


Plate Heat Exchanger

Source: Wiki

Thermosyphon Solar Water Heater



Thermosyphon solar water heaters work on the principle of natural convection, where hot water rises and cold water sinks.

The system consists of a solar collector and a storage tank. When sunlight falls on the collector, it heats up the fluid (a mixture of water and glycol or other antifreeze) circulating through it. As the fluid heats up, it rises through the collector and into the storage tank, where it displaces the cooler water at the bottom of the tank. The displaced cooler water then flows back into the collector to be heated again.

- No need for a heat exchanger as the required domestic hot water circulates directly through the panel.
- Normally the storage tank also contains an electric immersion heater for raising/keeping water temperature on cloudy days.

History of Thermosyphon Water Heater

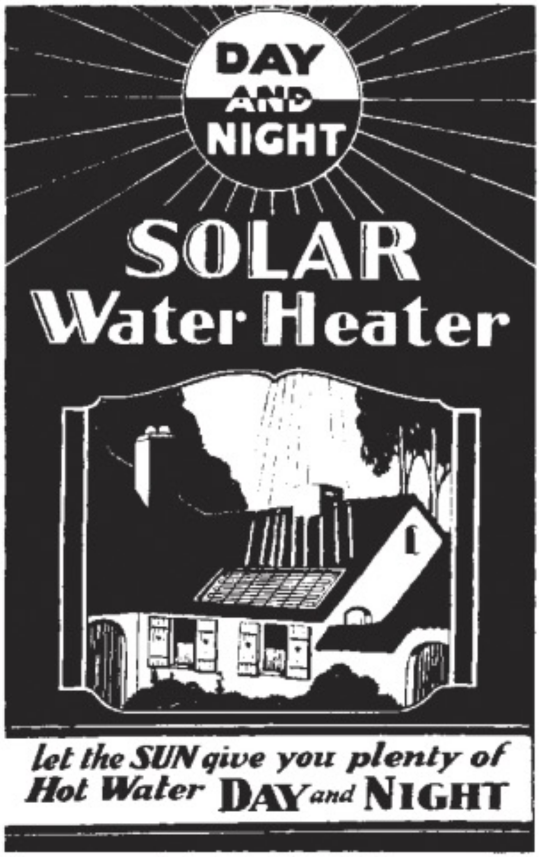
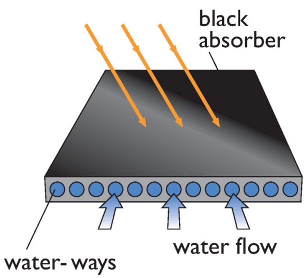


Figure: An advertisement for Bailey's solar water heaters in 1915.

- Thermosyphon water heater was patented in 1909 by William J. Bailey
- The system had an insulated tank, which could keep water hot overnight. Bailey called his business the 'Day and Night' Solar Water Heater Company
- Sold about 4000 systems before the local discovery of cheap natural gas in the 1920s that virtually closed his business

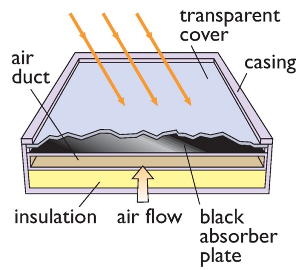
William Bailey

Varieties of Solar Collectors



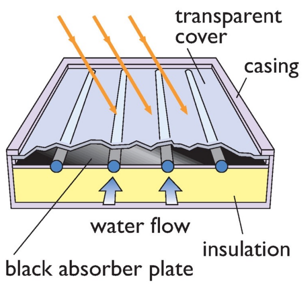
Unglazed, 0–10 °C rise

(a)



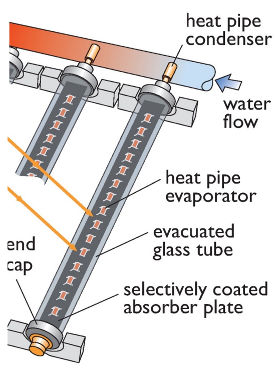
Flat plate (air), 0–50 °C rise

(b)



Flat plate (water), 0–50 °C rise

(c)



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

Water is a better heat transfer fluid than air because it can absorb and transfer more heat per unit volume and per unit time than air, due to higher specific heat capacity and thermal conductivity

(a) suitable for swimming pool heating, heat losses are relatively unimportant.

(b) not so common, mainly used for applications such as crop drying.

(c) mainstay of domestic solar water heating usually single glazed. With a more elaborate glazing system a higher temperature difference can be sustained.

(d) the absorber plate is a metal strip running down the center of each tube:

- heat losses due to convection are suppressed by a vacuum in the tube
- lower heat losses allow a better performance in winter, but more expensive

Solar District Heating

Sunmark A/S, Denmark

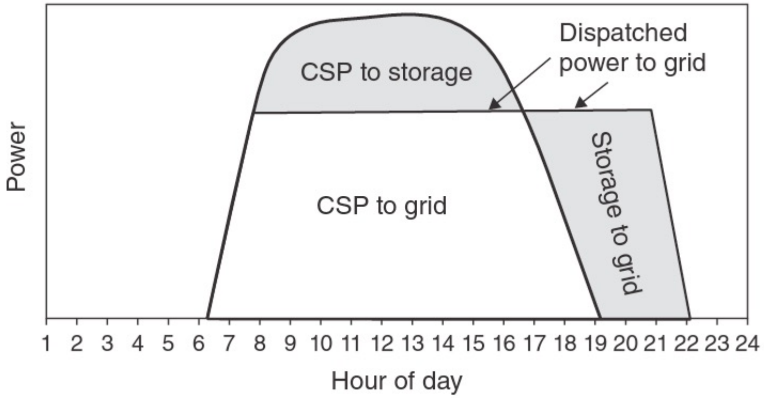
18,000 m^2 array of collectors in Marstal, Denmark.
A further 15,000 m^2 array and a 75,000 m^3 pit heat store have been stored to the left of this picture.
This supplies 50% of heating for 1650 households.

http://arcon-sunmark.com/sectors/district-heating

Concentrating Solar Power (CSP)

CSP technologies convert sunlight into thermal energy to run a heat engine to power a generator.

CSP can be used either as a *flexible provider of electricity* or *fossil-fuel backup or hybridization* that allows existing fossil fuel projects to run cleaner.



(a) Ivanpah Solar Power Facility (CA)

(b) SEGS (CA)

CSP (cont'd)

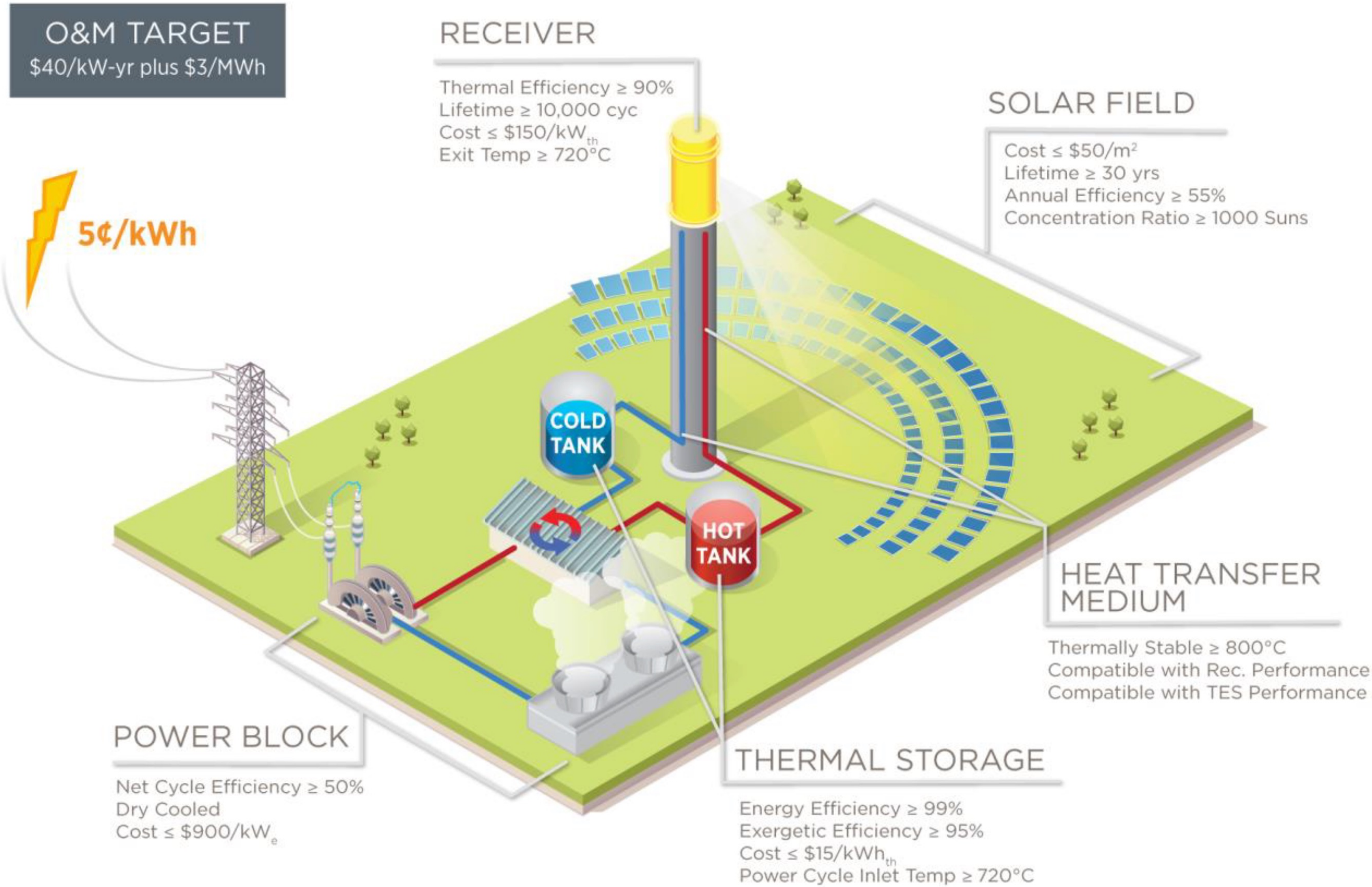
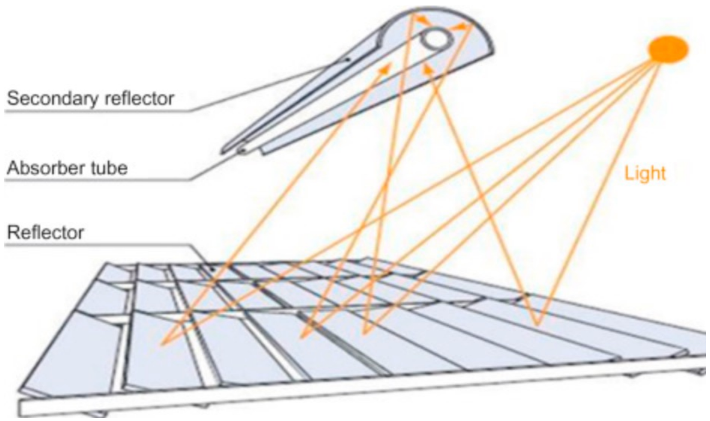
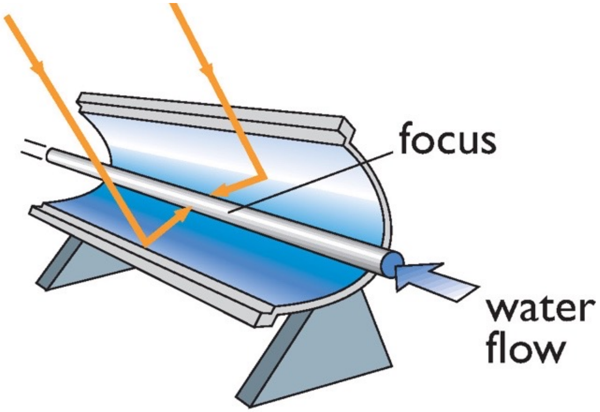


Figure source: DOE EERE office

Solar Collectors

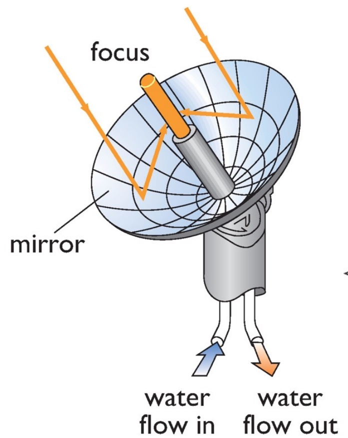


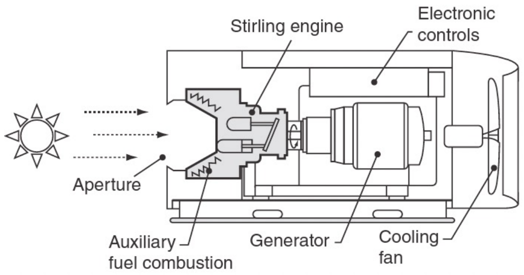


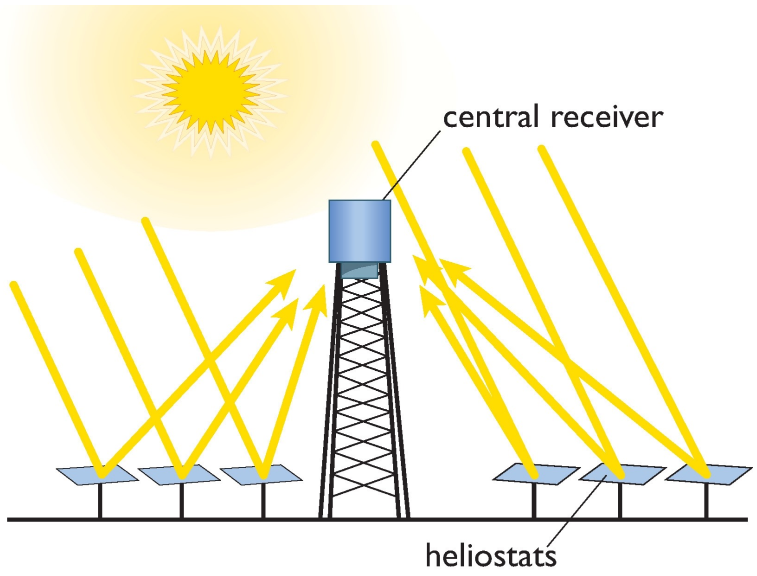
Linear Fresnel reflector (LFR): These mirrors are capable of concentrating the sun's energy to approximately 30 times its normal intensity.

Parabolic trough collector (PTC): Rays are focused onto a pipe running down the center of a trough. The pipe carries a high temperature heat transfer fluid (e.g., mineral oil).

Solar Collectors (cont'd)







Parabolic dish collector (PDC):
A large mirrored dish collects and concentrates the Sun's heat on to a receiver, which absorbs the heat and transfers it to fluid within a Stirling engine. The heat causes the fluid in the engine to expand against a piston or turbine.

Solar power tower (SPT):
The central receiver is a chamber where steam is produced directly used to drive a turbine. A heat transfer fluid is raised to a high temperature, to be pumped away to generate steam.

Technology Comparison

	Parabolic Trough	Solar Tower	Linear Fresnel	Dish-Stirling
Typical capacity (MW)	10-300	10-200	10-200	0.01-0.025
Maturity of technology	Commercially proven	Pilot commercial projects	Pilot projects	Demonstration projects
Key technology providers	Abengoa Solar, SolarMillennium, Sener Group, Acciona, Siemens, NextEra, ACS, SAMCA, etc.	Abengoa Solar, BrightSource, Energy, eSolar, SolarReserve, Torresol	Novatec Solar, Areva	
Technology development risk	Low	Medium	Medium	Medium
Operating temperature (°C)	350-550	250-565	390	550-750
Plant peak efficiency (%)	14-20	23-35*	18	30
Annual solar-to-electricity efficiency (net) (%)	11-16	7-20	13	12-25
Annual capacity factor (%)	25-28 (no TES) 29-43 (7h TES)	55 (10h TES)	22-24	25-28

Concentration Ratio

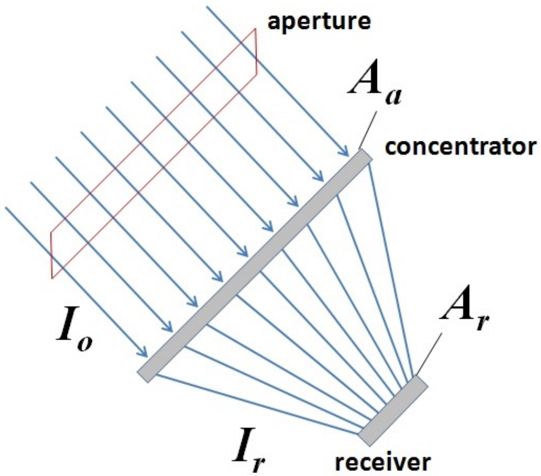


Fig: Schematic representation of light concentration process

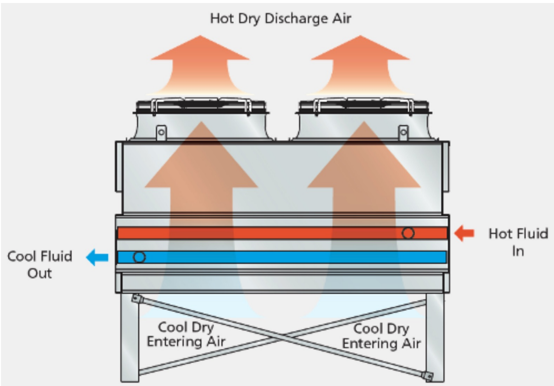
Concentration ratio (CR):

$$\mathrm{CR} = \frac{\text{Power per unit area at focus}}{\text{Power per unit area at aperture}}$$

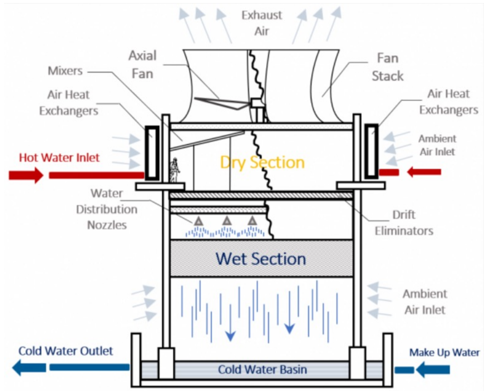
$$C_{geo} = \frac{\text{area of the aperture}}{\text{area of the receiver}} = \frac{A_a}{A_r}$$

- CR of a CSP solar collector can vary depending on the type of reflector and receiver used, as well as the design of the system. Typically, it ranges from 50 to 100. Some systems can achieve up to 1000.
- Higher CR also require more precise tracking systems and more complex and expensive reflectors, which can increase the cost of the system.

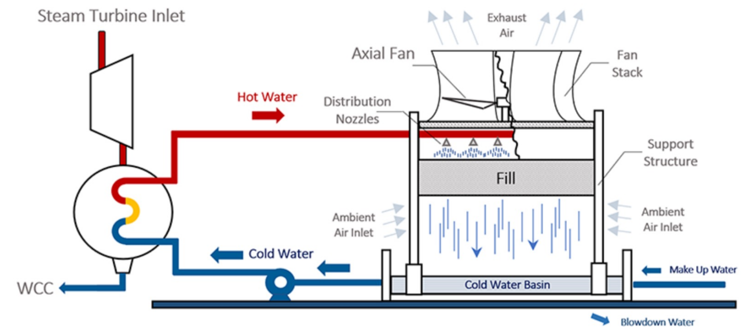
Types of Cooling Systems



Dry cooling



Hybrid cooling



Wet cooling

The main goal of cooling towers is to remove the excess heat and reject it to the outside environment.

Two main cooling towers: Closed-loop (dry cooling) vs Open-loop (wet cooling).

- Dry cooling: no direct contact between the fluid being cooled and ambient air.
- Wet cooling: the fluid has direct contact with ambient air.

Comparison of Cooling Systems

Cooling Systems

Air Cooled (Dry)

Advantages:

- No water consumption
- No water treatment required
- No cooling-tower or blowdown pond
- Lower O&M costs

Disadvantages:

- More expensive equipment
- Higher parasitic loads
- Poorer cooling at high dry-bulb temps
- (cycle efficiency falls)

Hybrid Cooling

Advantages:

- Reduced water consumption
- Potential for lower levelized energy cost
- compared to dry cooling
- Maintains good performance during hot weather

Disadvantages:

- Complicated system involving wet and dry cooling; often highest capital cost
- Same disadvantages of wet system, but to lesser degree

Wet (Evaporative) Cooling

Advantages:

- Lowest installed cost
- Low parasitic loads
- Best cooling (i.e., lowest cooling temperature), especially in arid climates; gives highest power cycle efficiency

Disadvantages:

- High water consumption
- Water treatment and blowdown disposal required
- Cooling tower plume in cold weather

TABLE 8.2 Water, Cost, and Performance Attributes Associated with Different CSP Cooling Systems

System	Criterion	Recirculating Evaporative	Air Cooling	Hybrid
Parabolic trough	Water consumption (gal/MWh)	800	78	100–450
	Performance penalty (%)	0%	4.5–5%	1–4%
	Cost penalty (%)	0%	2–9%	8%
Power tower	Water consumption (gal/MWh)	500–750	90	90–250
	Performance penalty (%)	0%	1–3%	1–3%
	Cost penalty (%)	0%		5%

Source: U.S. Department of Energy (2010).

LCOE

- The LCOE database: Providing cost-related data to help investors and developers make informed decisions.
- The auction database: Providing information about renewable energy projects that have been awarded contracts through auctions.

Heat Transfer Fluid (HTF)

- The HTF in a CSP system should have several properties: high thermal stability, low viscosity, high boiling point, low freezing point, high specific heat capacity, and good heat transfer characteristics.

- The most common types of heat transfer fluids used in CSP systems are synthetic oils, molten salts, and water/steam.

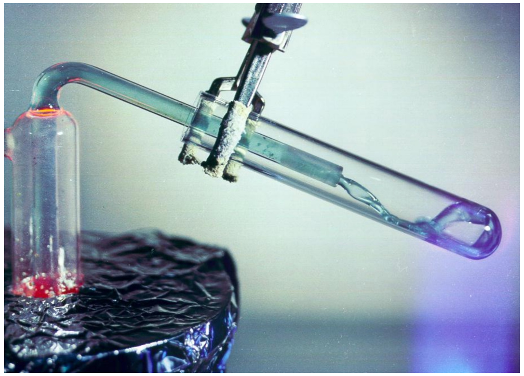
- Synthetic oils are used in low-temperature CSP systems, where the temperature of the heat transfer fluid does not exceed 400°C. Molten salts are commonly used in high-temperature CSP systems, where the temperature of the heat transfer fluid can reach up to 600°C.

- Using water as HTF is problematic as its pressure increases significantly with temperature. Using water may be worth it when a steam turbine is used as it avoids efficiency losses and extra costs in the exchanger.

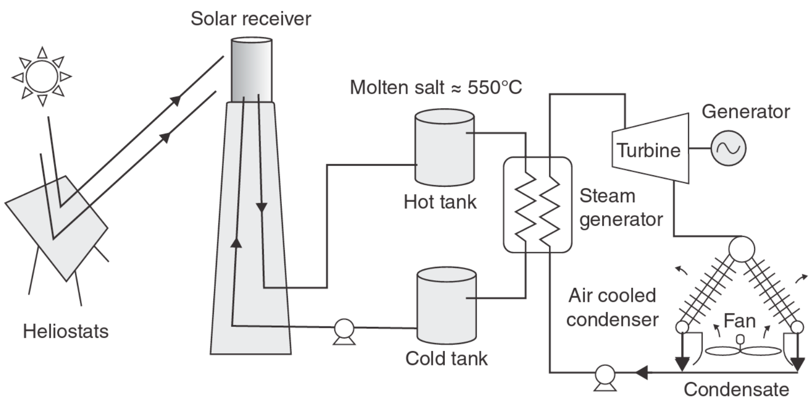
Oil vs Salt

Mineral oil: Any of various colorless, odorless, light mixtures of higher alkanes from a mineral source, particularly a distillate of petroleum

Molten salt: A mixture of nitrate salts. It is solid at standard temperature/pressure but enters the liquid phase due to elevated temperature



Direct System



Direct systems: the HTF used in the solar collector is also the working fluid that drives the power cycle. The HTF is heated by the concentrated sunlight and then passed directly to the turbine/engine to generate electricity.

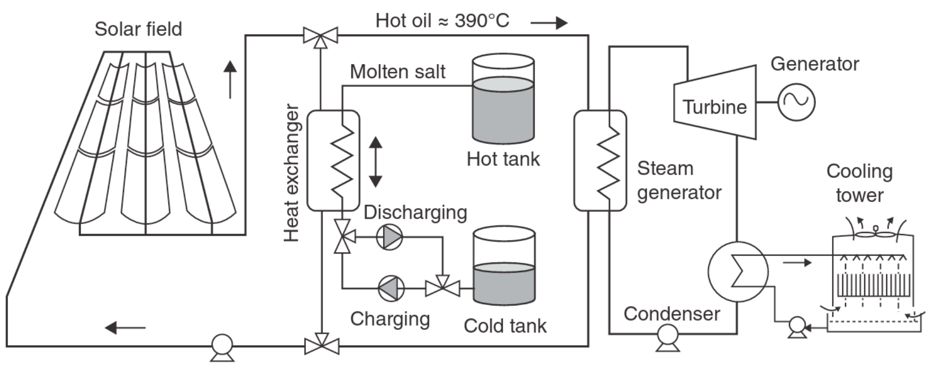
Pros:

- Simple and efficient system
- No need for heat exchangers, which reduces capital costs and system complexity
- High thermal efficiency, as there are no heat losses from the heat exchanger

Cons:

- Limited working temperature range, as the HTF must be able to drive the turbine or engine directly
- Limited flexibility in operation, as the system cannot operate at low loads or during periods of low solar radiation

Indirect Systems



Indirect systems: the HTF used in the solar collector is not the working fluid that drives the power cycle. Instead, the heat from the HTF is transferred to a secondary fluid (usually a molten salt or steam) through a heat exchanger, which then drives the power cycle.

Pros:

- Wide range of working temperatures: the secondary fluid can operate at higher temperatures than the HTF
- Greater flexibility in operation: operate at low loads and during periods of low solar radiation
- Lower maintenance costs: the HTF does not come into contact with the power cycle, reducing the risk of contamination and corrosion

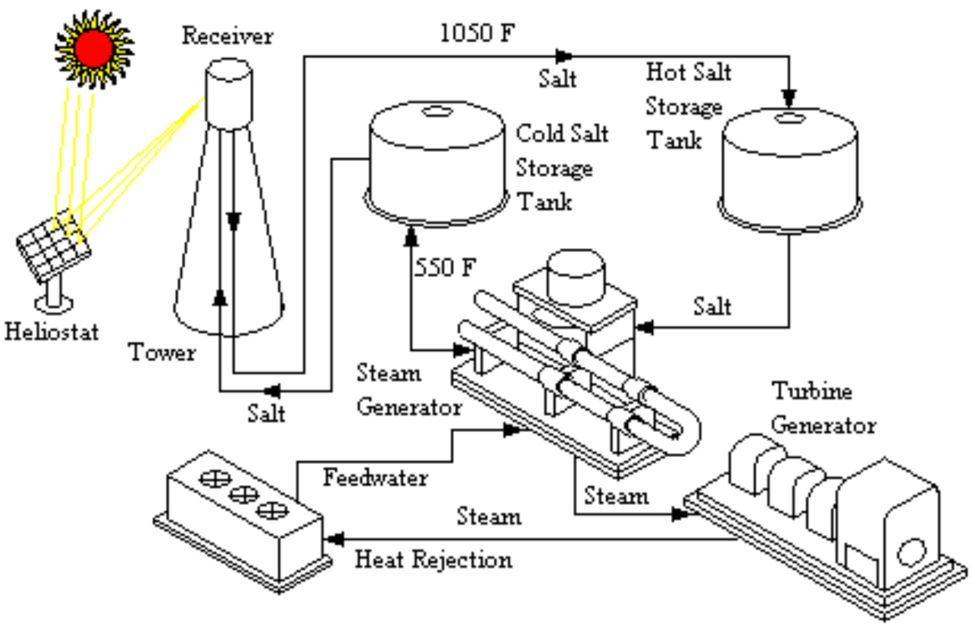
Cons:

- Lower thermal efficiency: heat losses from the heat exchanger
- Higher capital costs and system complexity: the need for a heat exchanger and a secondary fluid
- Increased risk of leakage and system failure: the higher number of components

Thermal Energy Storage (TES)

Molten salts can be employed as a TES to retain thermal energy

- A commercially used technology to store the heat collected by CSP
- Non-solar apps: as a heat-transport fluid in chemical & metals industries



1) The salt melts at 268 °F & is kept liquid at 550 °F in an insulated cold storage tank
2) The liquid salt is pumped through panels in a solar collector where being heated to 1,050°F. Then sent to a hot storage tank
3) Pumped to a steam generator for driving a turbine/generator
4) A 100MW turbine needs a tank of about 30 ft tall and 79 ft in diameter to drive it for 4 hours

Advantages of Molten Salts

Molten salts offer several advantages over high temperature oils:

- Allow for higher temperatures that reduces the volume of storage.
- More environmentally friendly: cheaper, nonflammable, nontoxic.
- Highly efficient: potential round-trip charging/discharging cycle efficiencies over 98% and standby thermal losses of about 0.03%/h.

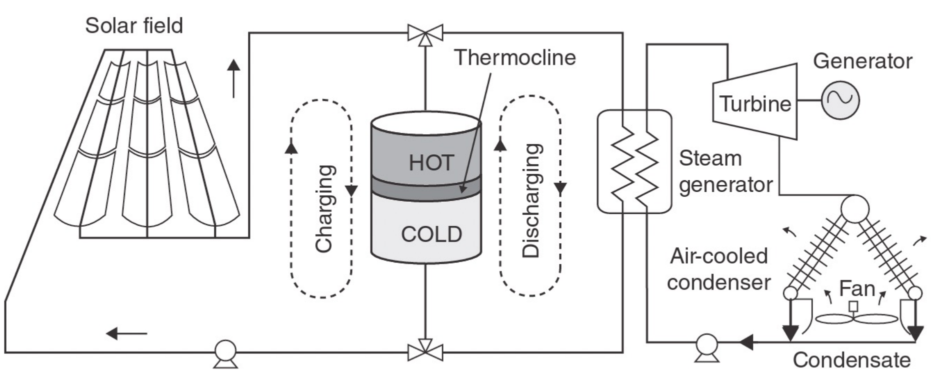


FIGURE 8.8 A direct, single-tank, thermocline, molten salt storage system.

Fig: Single-tank thermocline storage. Besides molten salt, a low-cost filler material such as quartzite rock in combination with silica sand would occupy much of the volume (to inhibit vertical mixing of the layers while reduce the fluid volume required).

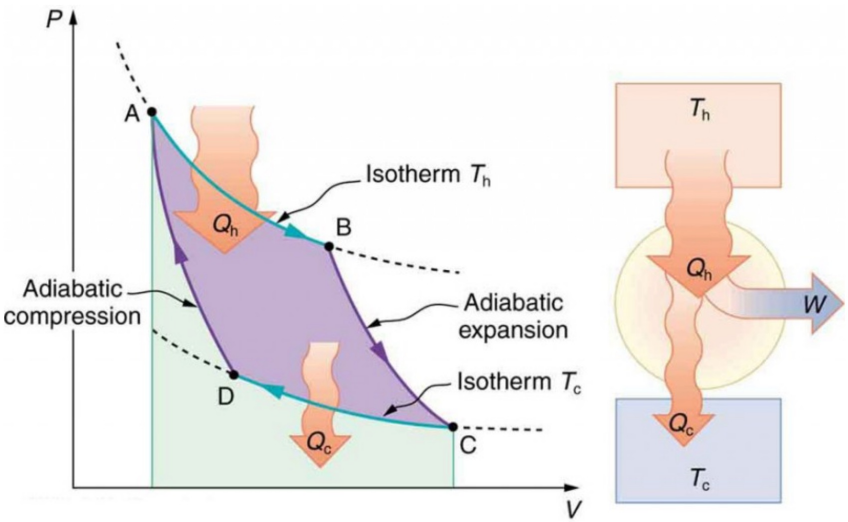
Types of TES Systems

- **Sensible (single-phase) storage: achieved by heating the storage medium and increasing its energy content but not changing state during accumulation.**
  - Liquids: liquid sodium, molten salt or pressurized water
  - Solids: ceramic, graphite, concrete

- **Phase-change materials:** Use latent heat to store energy (e.g., molten salts, metallic alloys). Phase change materials have the benefit of high thermal capacity but have the drawback of degrading performance after a number of freeze-melt cycles.

- **Thermochemical storage:** Converting solar energy into chemical bonds (e.g., decomposition or synthesis, redox reactions).

Thermal Efficiency



Pressure-Volume (PV) diagram of a Carnot cycle: employing only reversible isothermal and adiabatic processes.

- Heat transfer Q_h occurs into the working substance during the isothermal path AB, which takes place at constant temperature T_h.
- Heat transfer Qc occurs out of the working substance during the isothermal path CD, which takes place at constant temperature Tc.
- The net work output W equals the purple area.

$$\text{Thermal efficiency } \eta = \frac{\text{net work output}}{\text{total hear input}} = \frac{W}{Q_H} = \frac{Q_H - Q_C}{Q_H} = 1 - \frac{Q_C}{Q_H}$$

Source: courses.lumenlearning.com

Carnot's Theorem

The efficiency of even the best heat engines is low (<50% and often far below). Modern cogeneration, combined cycle and energy recycling schemes are beginning to use this heat for other purposes.

Three causes of inefficiency:

1) There is an overall theoretical limit to the efficiency of any heat engine due to temperature, called the Carnot efficiency.
2) Inherent irreversibility of the engine cycle.
3) The nonideal behavior of real engines, such as mechanical friction and losses in the combustion process

- Reversible engines are the ones that can be reversed or whose process if reversed will not cause any loss of energy
- Irreversible engines are the ones that undergo loss of energy in due course of operation.

As a consequence of the 2nd Law of Thermodynamics, **Carnot's Theorem** says that no irreversible engine is more efficient than a Carnot engine operating between the same two thermal reservoirs.

$$\frac{Q_C}{T_C} \geq \frac{Q_H}{T_H} \quad \Rightarrow \quad \eta_{\max} = 1 - \frac{T_C}{T_H}$$

CSP Requires Interdisciplinary Solutions

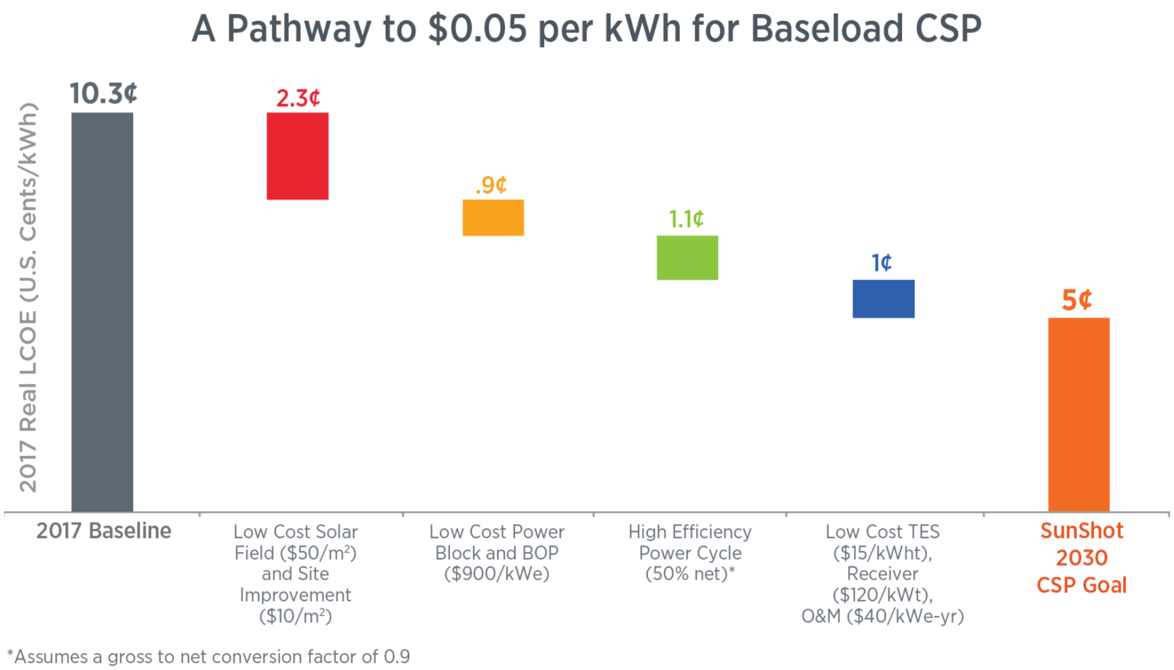


Fig: Two Power Tower plants in southern Spain (2009)

There is no single CSP challenge but rather a series of challenges of:

- heat transfer, fluid mechanics, thermodynamics,
- optical physics, materials science, extreme automation in the solar field, corrosion mitigation, advanced manufacturing, thermo-mechanical engineering design, low-cost sensors & control, and
- predictive operations and maintenance, among others.

Figure source: DOE SETO FOA