EN671: Solar Energy Conversion Technology

Solar Concentrating Collectors

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Concentrating collector technologies and working principles

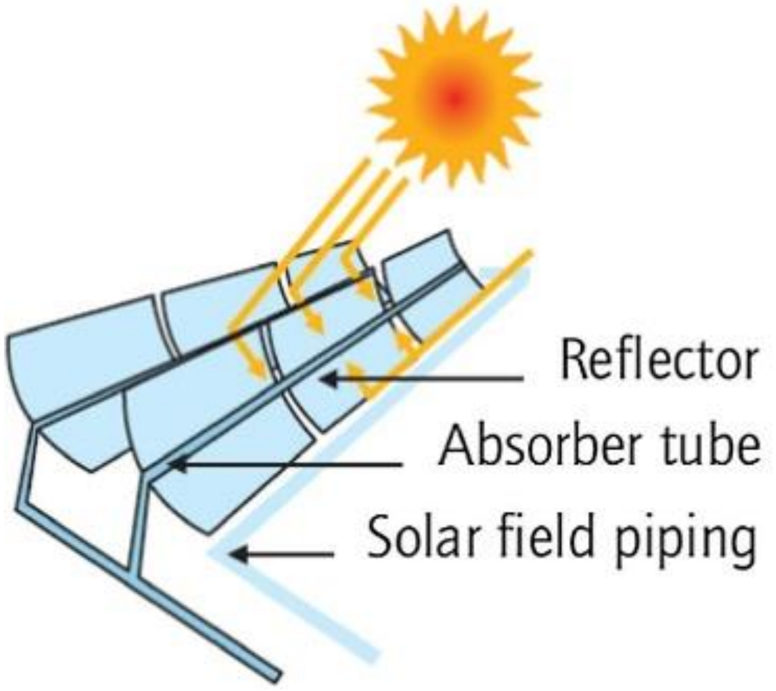
Concentric solar technology based on application

Concentric Solar Technology (CST)

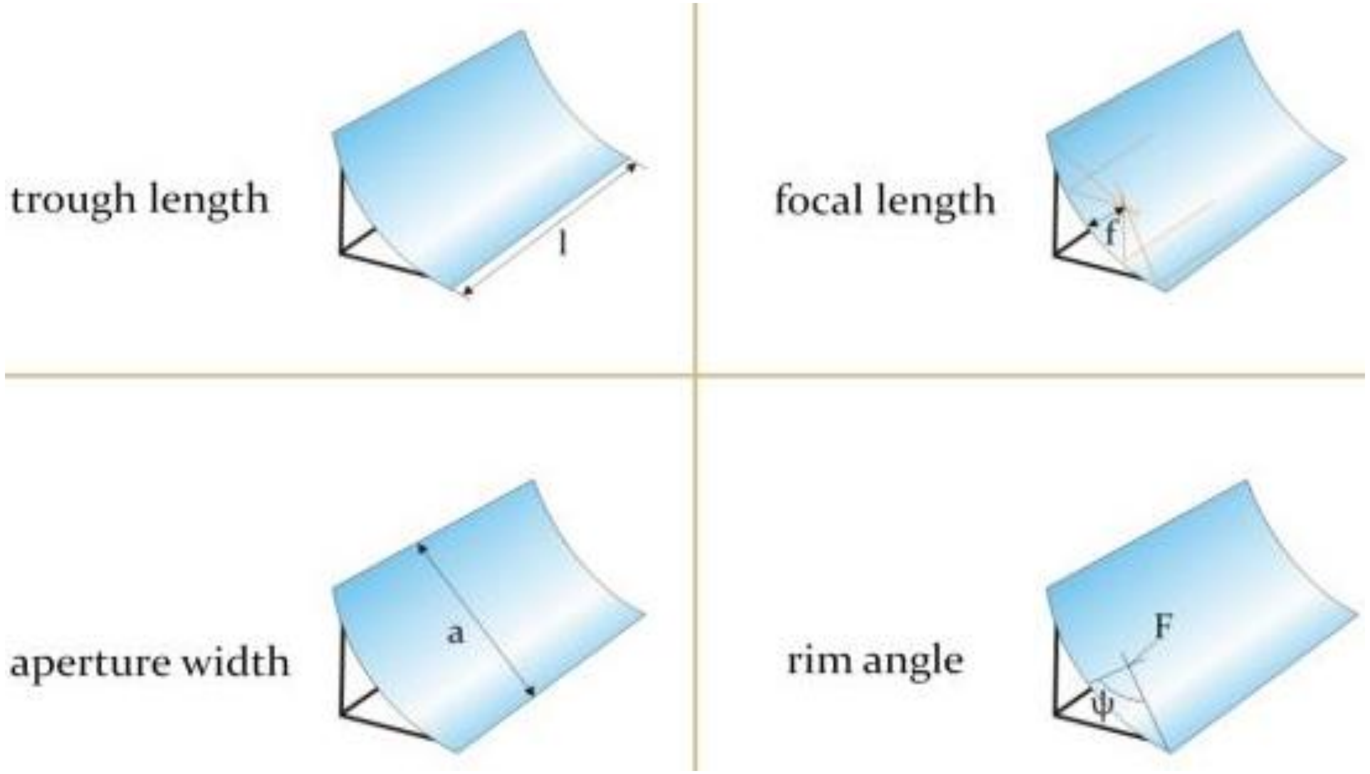
- Parabolic trough
- Dish Stirling
- Central Tower
- Fresnel Collector

Parabolic trough

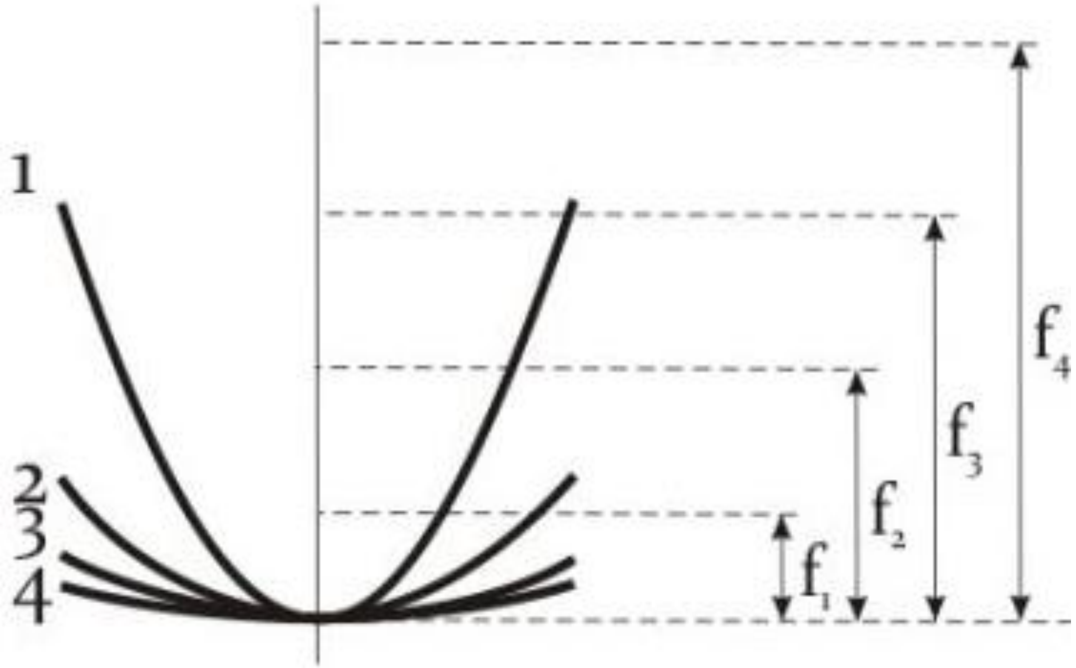
- Temperature: 400 ^{o}C
- Line focusing
- Concentrators: Parabolic mirrors
- Linear receiver tube
- Water consuming
- Heat Storage feasible
- Most commercialized
- Good for hybrid option
- Requires flat land
- Good receiver efficiency but low turbine efficiency



Parameters for solar parabolic trough collector technology



Geometrical parameters of PTC



Focal length as shape parameter

Components of parabolic trough systems

- Parabolic reflectors (mirrors)
- Receiver tube
- Metal support structure
- Tracking system (includes the drive, sensors, and controls)

Applications

- Thermal energy for industrial processes (e.g., food industry, petro-chemical industry, etc.)
- Electricity generation.

Limitations

- Degradation of thermal oil at higher temperature.

Parabolic trough system

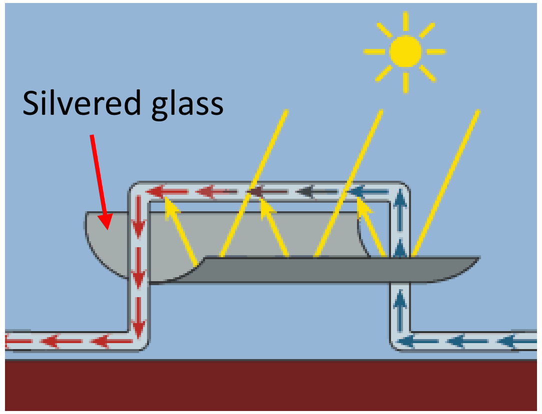
- ❑ Parabolic troughs are devices that are shaped like the letter “U”.
- ❑ The troughs concentrate sunlight onto a receiver tube that is positioned along the focal line of the trough.

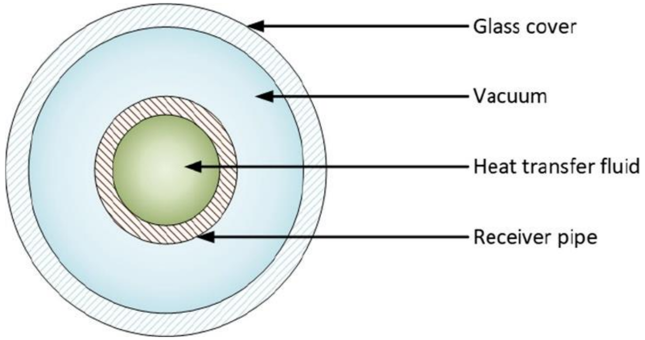
- ✓ Aperture area: 1 – 60 m^2
- ✓ Width: 1 to 6 m
- ✓ C: 10 to 80
- ✓ Rim angle: 70 to 120^o

- ✓ Absorber tube: 2.5 – 5 cm
- ✓ Tube material: Steel/copper

Coated with heat resistant black paint

- ✓ Gap between glass cover and absorber: 1 to 2 cm



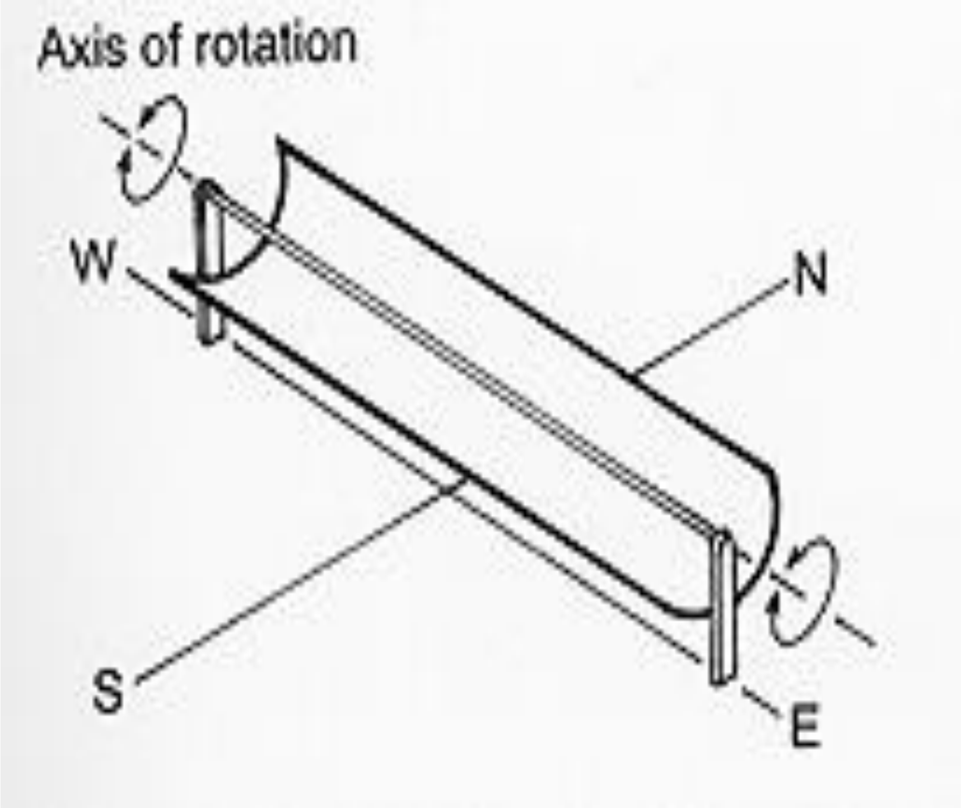


CSP Absorber tube scheme

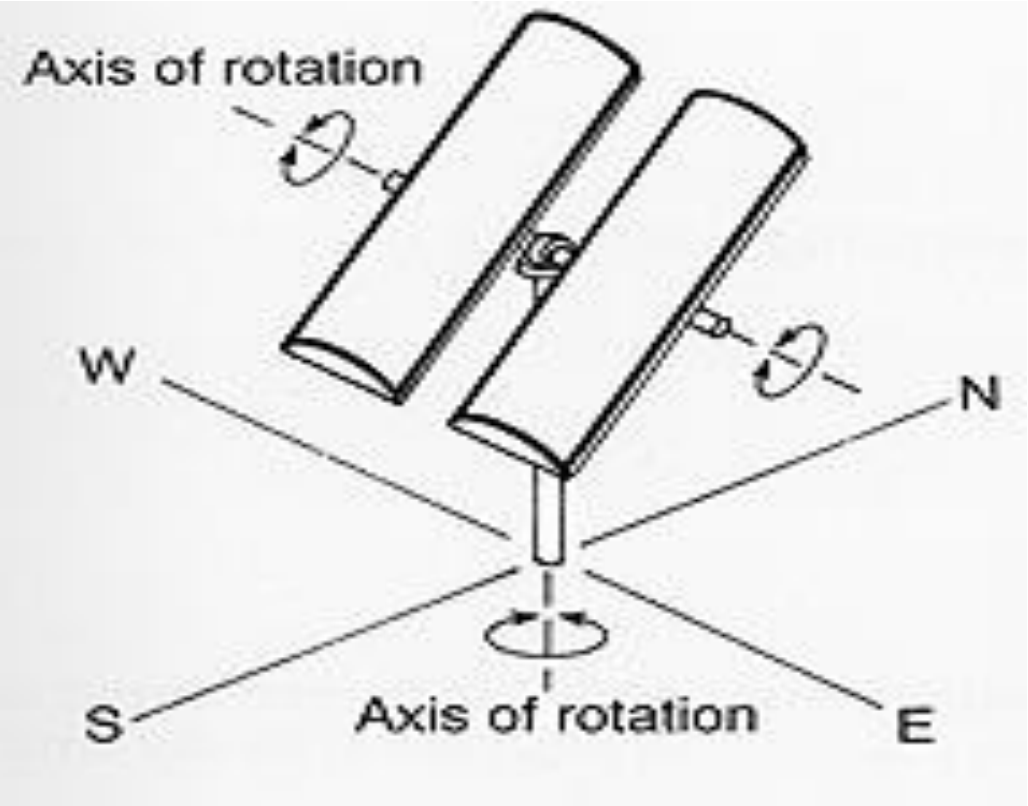
Crossection of parabolic trough

Parabolic trough system

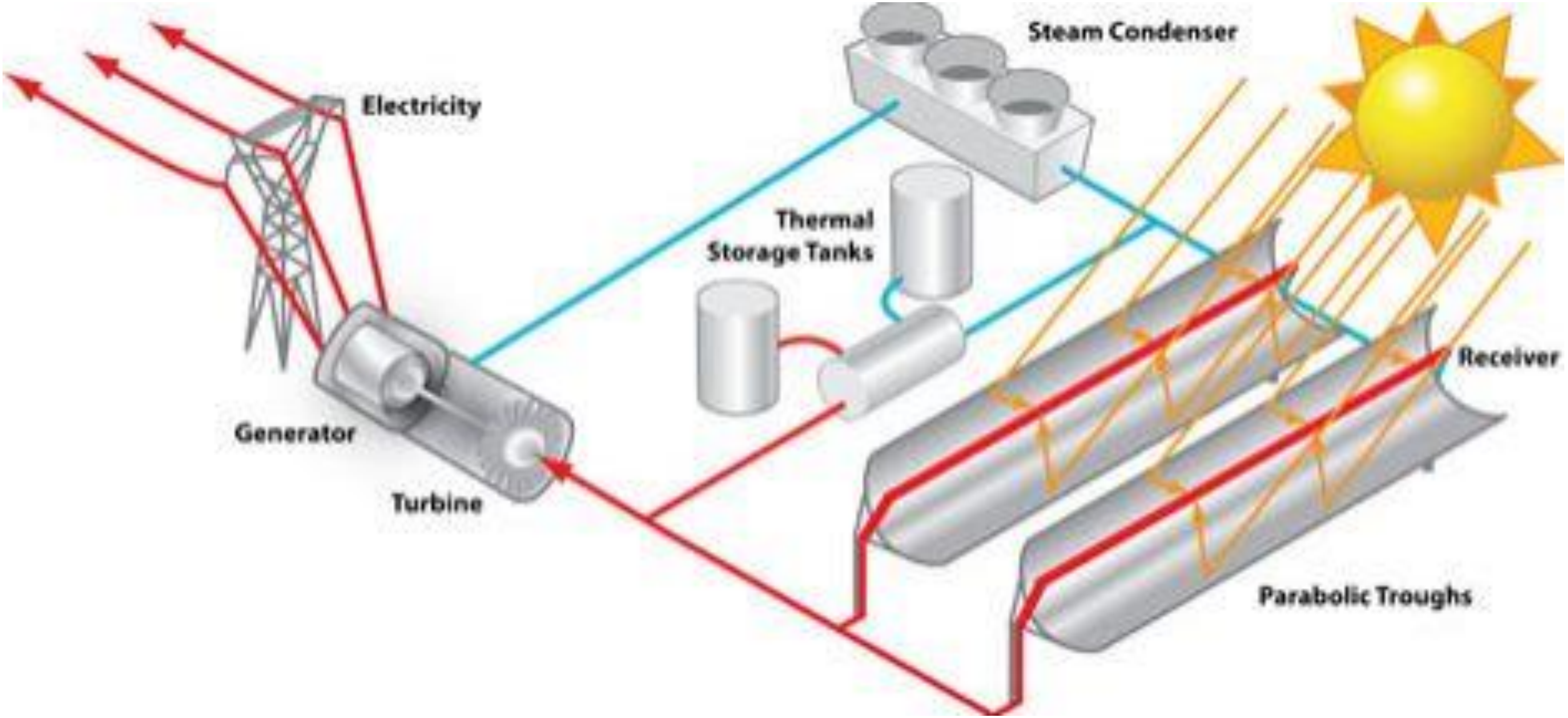
Parabolic troughs often use single-axis or dual-axis tracking.



Single Axis Tracking Parabolic Trough with Axis Oriented E-W



Two Axis Tracking Concentrator



Schematic of Parabolic trough for power generation

Temperatures at the receiver can reach 400 °C and produce steam for generating electricity. In California, multi-megawatt power plants were built using parabolic troughs combined with gas turbines.

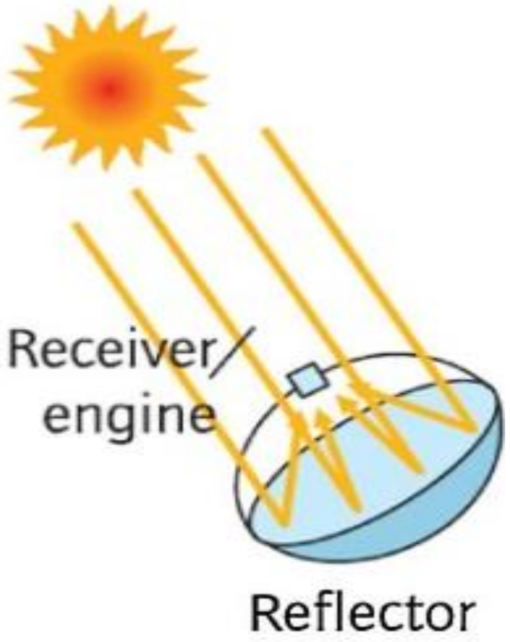
Parabolic trough system for power generation

Concentric solar technology based on application

Concentric Solar Technology (CST)

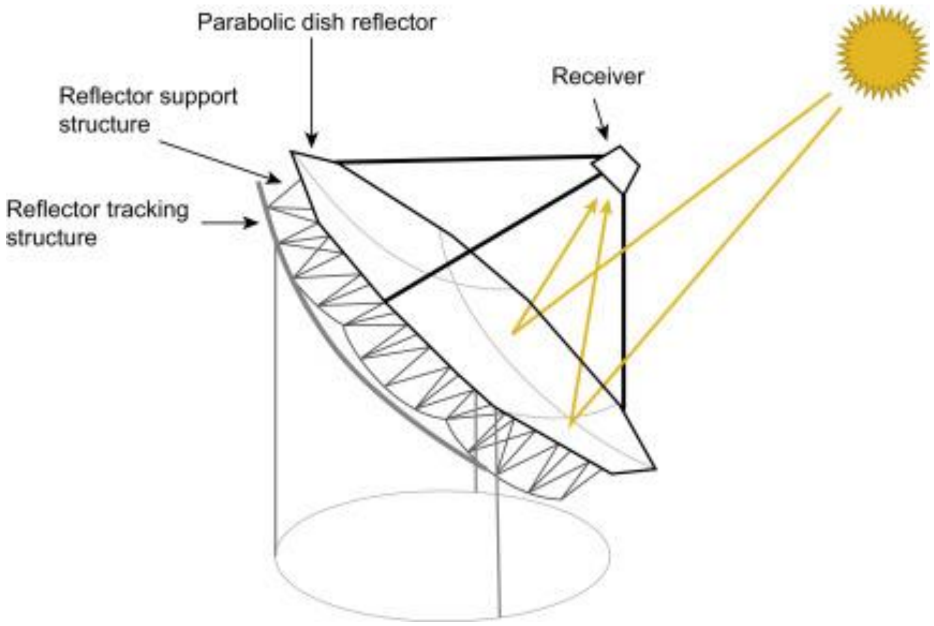
- Parabolic trough
- Dish Stirling
- Central Tower
- Fresnel Collector

- Temperature: 700-800 ^{o}C
- Point Focusing
- Uses Dish concentrator
- Stirling Engine
- Generally 25 kW units
- High Efficiency ~ 30 %
- Dry cooling
- Heat storage difficult
- Commercially under development
- Dual axis tracking



Parabolic dish system

A parabolic dish collector is similar in appearance to a large satellite dish, but has mirror-like reflectors and an absorber at the focal point. It uses a dual axis sun tracker.



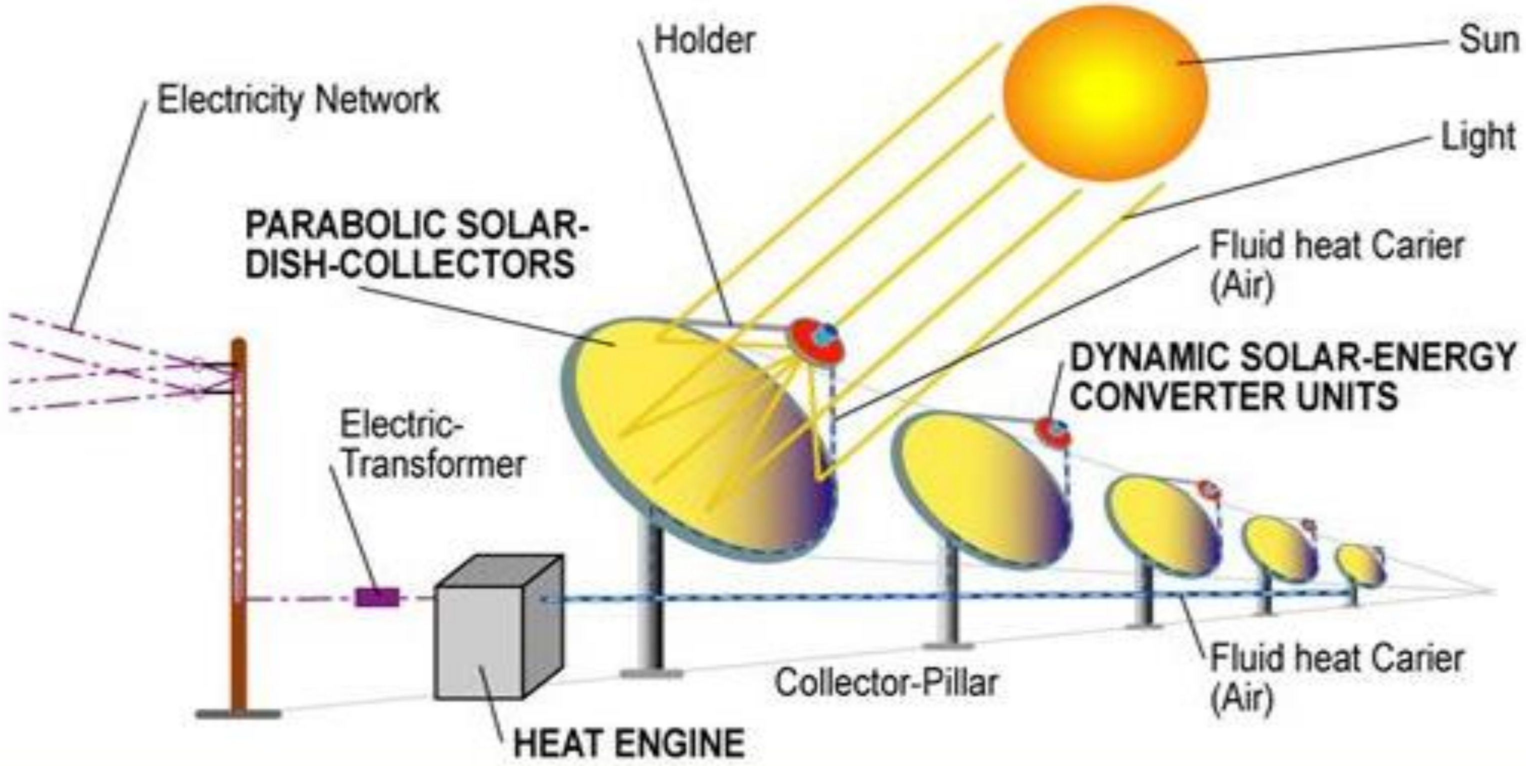
Schematic of parabolic dish collector

The Parabolic dish collector

Parabolic dish collector with a mirror-like reflectors and an absorber at the focal point [Courtesy of SunLabs - Department of Energy]

Parabolic dish system: Key features

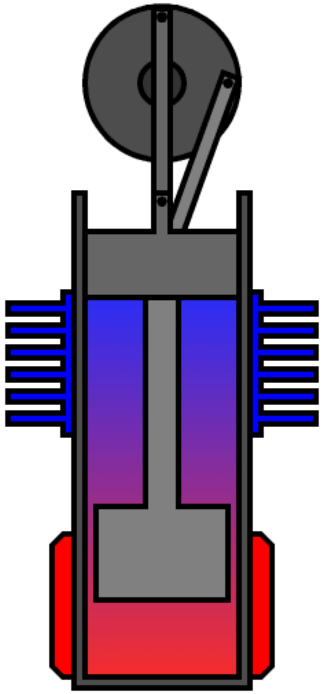
- Uses a computer to track the sun and concentrate the sun's rays onto a receiver located at its focal point.
- A heat engine, such as a Stirling engine, is linked to the receiver to generate electricity.
- Temperature reaches up to 1000 °C at the receiver, and achieve the very high efficiency for converting solar energy to electricity.



Schematic of parabolic dish collector system for power generation

Parabolic dish system: Working principle

- Receiver is integrated into a high-efficiency "external" combustion engine.
- Engine has thin tubes containing H_2 or He gas.
- Concentrated sunlight falls on the receiver, it heats the gas in the tubes to very high temperatures, which causes hot gas to expand inside the cylinders.
- The expanding gas drives the pistons. The pistons turn a crankshaft, which drives an electric generator.
- The receiver, engine, and generator comprise a single, integrated assembly mounted at the focus of the mirrored dish.



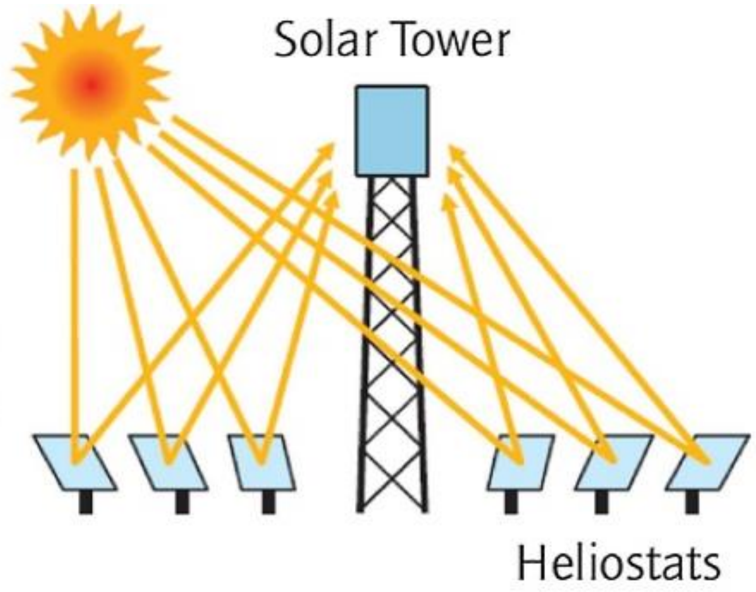
Solar parabolic dish stirling engine

Concentric solar technology based on application

Concentric Solar Technology (CST)

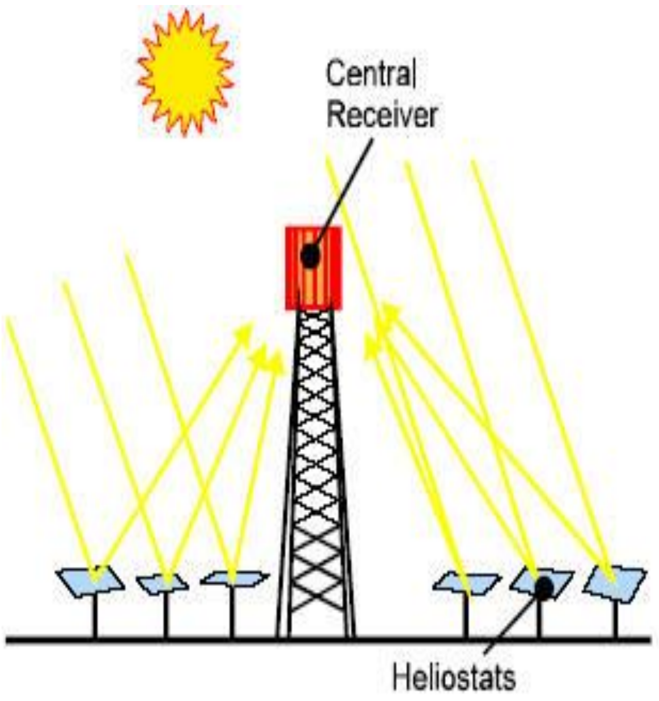
- Parabolic trough
- Dish Stirling
- Central Tower
- Fresnel Collector

- Temperature: 600-800 ^{o}C
- Point Focusing
- Flat concentratic mirrors
- Central receiver
- Water consuming
- Heat storage capability
- Feasible on non-flat sites
- High thermodynamic efficiency
- Commercially proven



Central Tower System

- A heliostat uses a field of dual axis sun trackers that direct solar energy to a large absorber located on a tower.
- A power tower has a field of large mirrors that follow the sun's path across the sky.
- Molten salt retains heat efficiently, so it is used to store heat for a long time.



Schematic Heliostat Power tower system

Heliostat Power tower system

Analysis of Central Power receiver System

The mirrors have to be laid out in such a manner that incident or reflected radiation associated with one heliostat is not blocked by the neighboring heliostat.

$$\boxed{NA_m = \psi A_g} \qquad \text{(a)}$$

Taking the energy balance on the absorber, the useful het gain rate:

$$\boxed{q_u = I_b\left[\sum_{j=1}^{N} r_{bj}\right]\rho\,\tau\,\alpha\,A_m - U_l A_p\left(T_{pm} - T_a\right)} \qquad \text{(b)}$$

Average tilt factor,

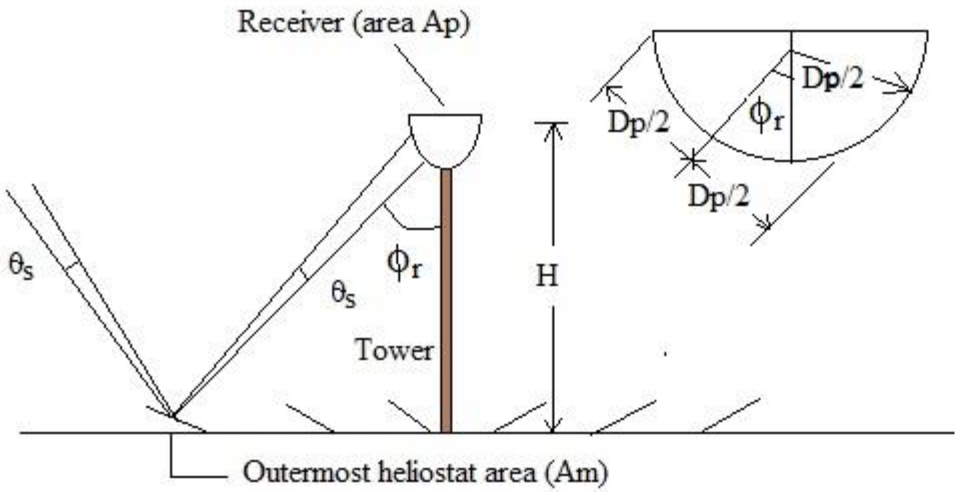
$$\boxed{(r_b)_{av} = \frac{1}{N}\sum_{j=1}^{N} r_{bj}} \qquad \text{(c)}$$

Utilizing eqs.(a) and (c), in eq.(b)

$$\boxed{\begin{aligned} q_u &= I_b\,(r_b)_{av}\,NA_m\rho\tau\alpha - U_l A_p\left(T_{pm} - T_a\right) \\ \Rightarrow q_u &= I_b\,(r_b)_{av}\,\psi A_g\rho\tau\alpha - U_l A_p\left(T_{pm} - T_a\right) \end{aligned}} \qquad \text{(d)}$$

$$\boxed{q_u = \psi A_g\left[I_b\,(r_b)_{av}\,\rho\tau\alpha - \frac{U_l}{C}\left(T_{pm} - T_a\right)\right]} \qquad \text{(e)}$$

- ✓ For circular mirror: $A_m = \pi w^2 / 4$
- ✓ For square mirror: $A_m = w^2$
- ✓ Ground area : A_g
- ✓ Fraction of ground area covered: ψ
- ✓ No, of Mirrors: N
- ✓ Surface area of the absorber: A_p
- ✓ Tower height: H



Concentration ratio: $C = N\,A_m / A_p = (\psi\,A_g / A_p)$

✓ **Assuming the mirror field is circular with the tower at the centre**

Distance between the outermost mirror and the absorber is $= \dfrac{H}{\cos\varphi_r}$

Size of the image at the absorber

(If the mirrors are flat)

$$L_i = \frac{H}{\cos\phi_r}(\theta_s - \theta_e) + w$$

θ_s = Angle subtended by the sun at the earth

θ_e =Total angular error associated with the reflection due to factors like mirror surface imperfections and mirror orientation

If the mirrors are suitably dished,

(Spread of the image due to the mirror span could be eliminated)

$$L_i = \frac{H}{\cos\varphi_r}(\theta_s - \theta_e)$$

Area of the absorber

$$A_p = \frac{\pi}{2} D_p^2 \left(1 + \sin\phi_r - \frac{\cos\phi_r}{2}\right)$$

$$A_p = \frac{\pi}{2}\left\{\frac{H}{\cos\phi_r}(\theta_s + \theta_e) + w\right\}^2 \left(1 + \sin\phi_r - \frac{\cos\phi_r}{2}\right)$$

Vant-Hull and Hildebrandt suggested absorber shape could be spherical segment with a conical section

The concentration ratio:

$$C = \frac{NA_m}{\frac{\pi}{2}\left\{\frac{H}{\cos\phi_r}(\theta_s + \theta_e) + w\right\}^2 \left(1 + \sin\phi_r - \frac{\cos\phi_r}{2}\right)} = \frac{\psi\pi H^2 \tan^2\phi_r}{\frac{\pi}{2}\left\{\frac{H}{\cos\phi_r}(\theta_s + \theta_e) + w\right\}^2 \left(1 + \sin\phi_r - \frac{\cos\phi_r}{2}\right)}$$

Problem 1: In a central receiver collector, the height of the tower is 150 m, rim angle is 50° and the diameter of the mirrors is 4.5 m. Find

(a) the size of the image formed by the outermost mirror at the receiver

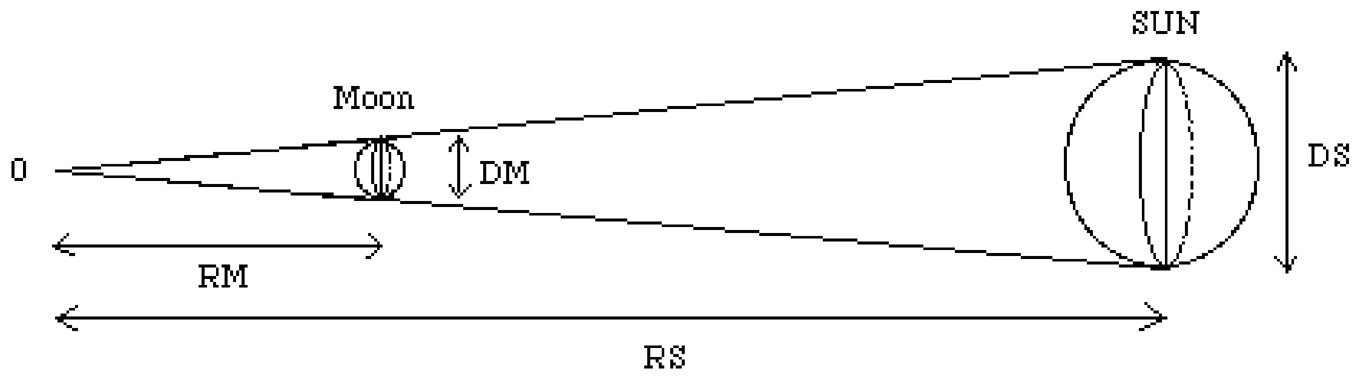
(b) The area of the absorber and

(c) Concentration ratio

Calculate the above for (i) flat mirrors, and (ii) dished mirrors.

Take $$\psi = 0.38 \; and \; \theta_e = 0.002 \; radians$$

$$\alpha_{radian} = \alpha_{degree} \times \frac{\pi}{180^0}$$



Use the following formulas

$$L_i = \frac{H}{\cos\phi_r}(\theta_s + \theta_e) + w$$

$$A_p = \frac{\pi}{2} \times D_p^{\,2} \times \left(1 + \sin\phi_r - \frac{\cos\phi_r}{2}\right)$$

$$C = \frac{\psi \pi H^2 \tan^2\phi_r}{A_p}$$

Solution:

(i) For Flat mirrors

$$L_i = \frac{150}{\cos 50^0}\left(\frac{32\pi}{60\times 180}+0.002\right)+4.5 = 7.14\ m$$

$$A_p = \frac{\pi}{2}\times 7.14^2 \times\left(1+\sin 50^0 - \frac{\cos 50^0}{2}\right) = 115.67\ m^2$$

$$C = \frac{0.38\times\pi\times 150^2 \tan^2 50^0}{115.67} = 330$$

(ii) For Dished mirrors

$$L_i = \frac{150}{\cos 50^0}\left(\frac{32\pi}{60\times 180}+0.002\right) = 2.64\ m$$

$$A_p = \frac{\pi}{2}\times 2.64^2 \times\left(1+\sin 50^0 - \frac{\cos 50^0}{2}\right) = 15.82\ m^2$$

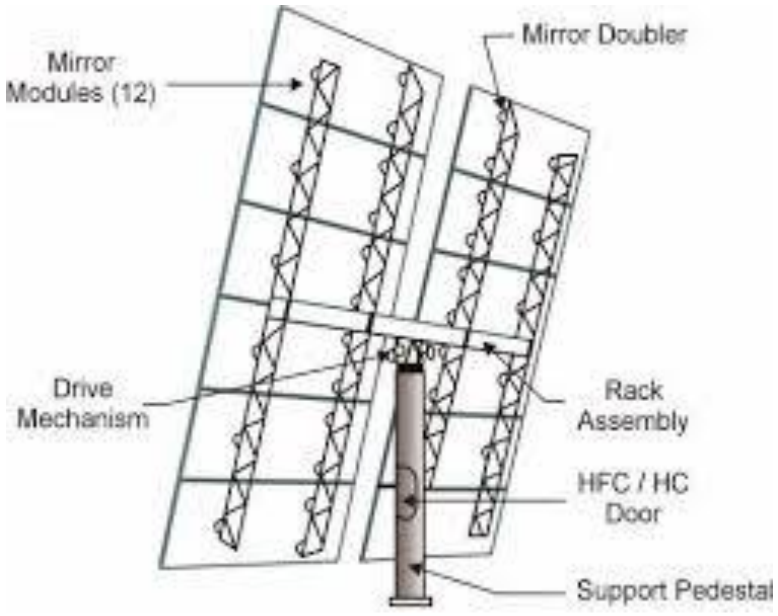
$$C = \frac{0.38\times\pi\times 150^2 \tan^2 50^0}{15.82} = 2412$$

Power tower system with heliostats for power generation

Molten salt storage system

- Best suited for large scale applications: 30-400 MW.
- Liquid salt is pumped from a storage tank through the receiver where it achieves about 1000 ^{o}C.
- Hot salt is pumped to a steam generating system that produces superheated steam for a conventional Rankine cycle turbine generator system.

Heliostats

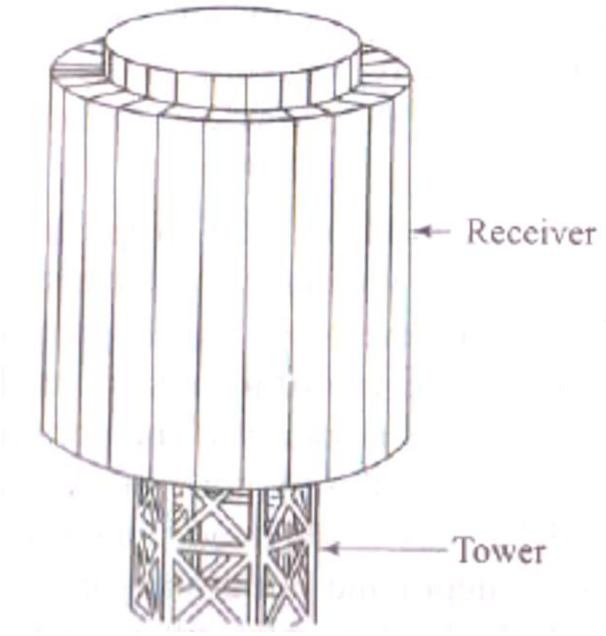


- 10 MWe, Barstow solar one, has 1818 heliostats, height 80 m
- Each heliostat (1m x 3m) has an assembly of 12 slightly concave glass mirrors mounted on a support structure, gear drive to control azimuth as well as elevation, reflective area 39.3 m^2

Average reflectivity: 0.903, reduced to 0.82 (due to dirt)

Tower Receiver

- Ability to accept large and variable heat flux (100-1000 kW/m^2) results in high temperature, high thermal gradient, and high stresses.
- Two types: external type and cavity type
- In a cavity receiver, the solar flux enters through one or more small apertures in an insulated enclosure.



Schematic of tower receiver

Central Tower System

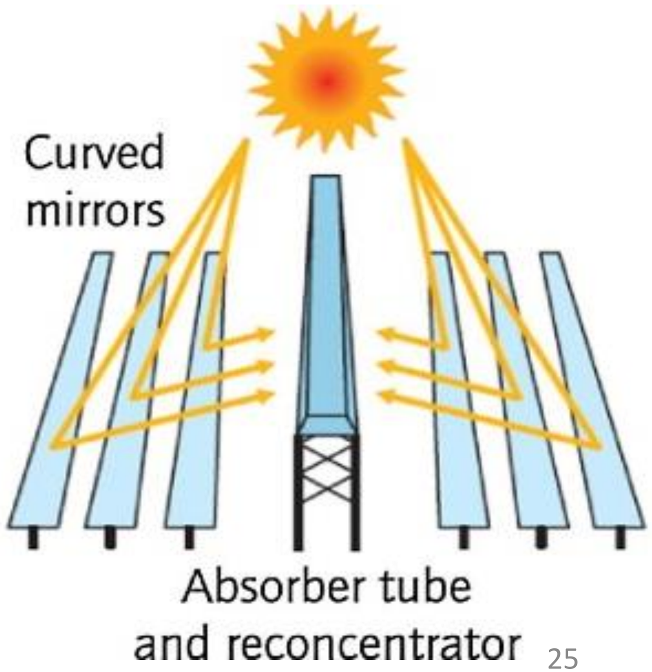
Name	Location	Output MW (e)	Heat Transport Fluid	Completion date
SSPS	Almeria (Spain)	0.5	Sodium	1981
CESA-I Eurelios	Almeria (Spain) Adrano (Italy)	1.0 0.7	Steam Steam	1983 1981
Sunshine THEMIS	Nio (Japan) Targasonne (France)	0.8 2.5	Steam Molten Salt	1981 1982
Solar One	Barstow (USA)	10	Steam	1982

Concentric Solar Technology based on application

Concentric Solar Technology (CST)

- Parabolic trough
- Dish Stirling
- Central Tower
- Fresnel Collector

- Temperature: 500 ^{o}C
- Line Focusing type
- Linear Receiver
- Flat or curved concentratic mirrors (C ~ 10-70)
- Heat Transfer Fluid: Thermal oil, Molten salt, Pressurized water
- Commercially under development
- Storage ability

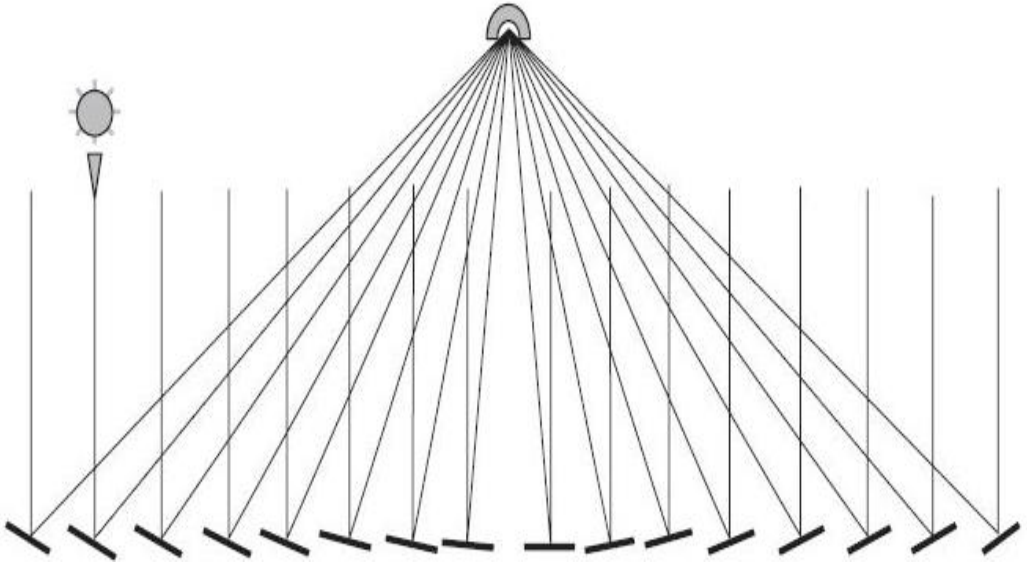


Linear Fresnel Collector System

An optical device for concentrating light that is made of concentric rings that are faced at different angles so that light falling on any ring is focused to the same point.

Components

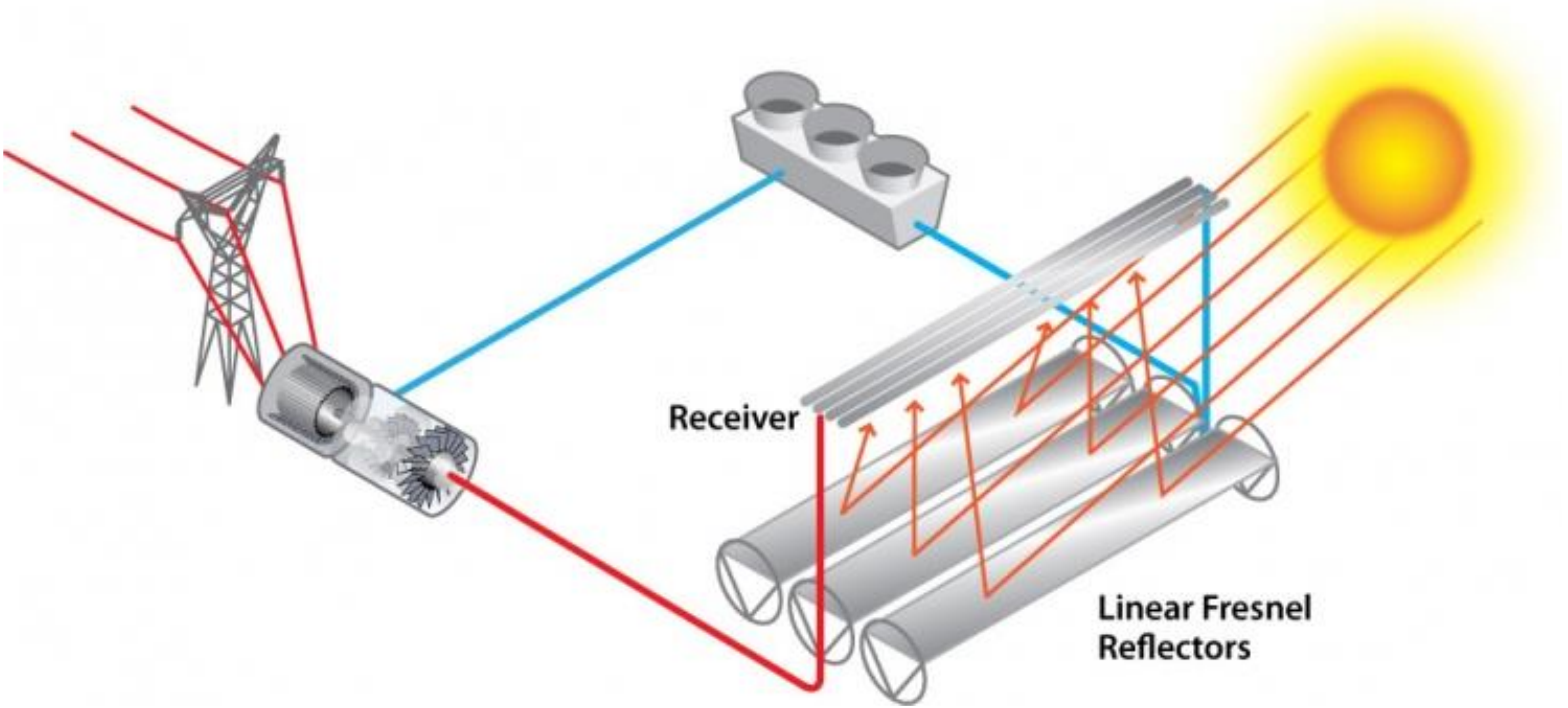
- Collector: Fresnel Lens or mirror
- Receiver:
  - Secondary concentrator
  - Absorber tube
- Tracking mechanism
- Steam Drum



Schematic of Linear Fresnel reflector configuration

Linear Fresnel reflector system

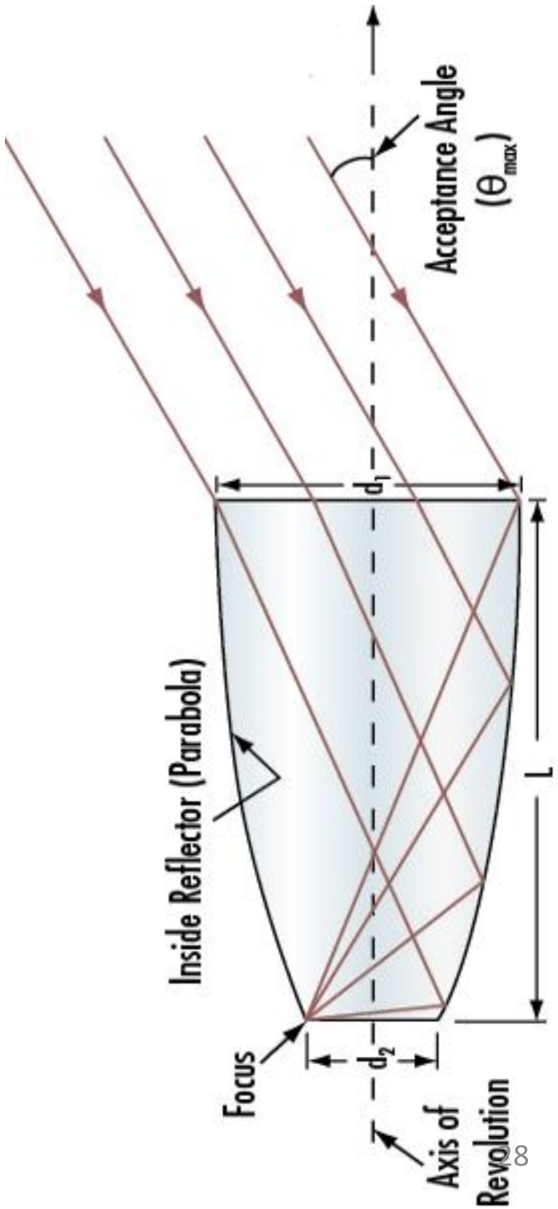
Linear Fresnel Collector System: Working principle



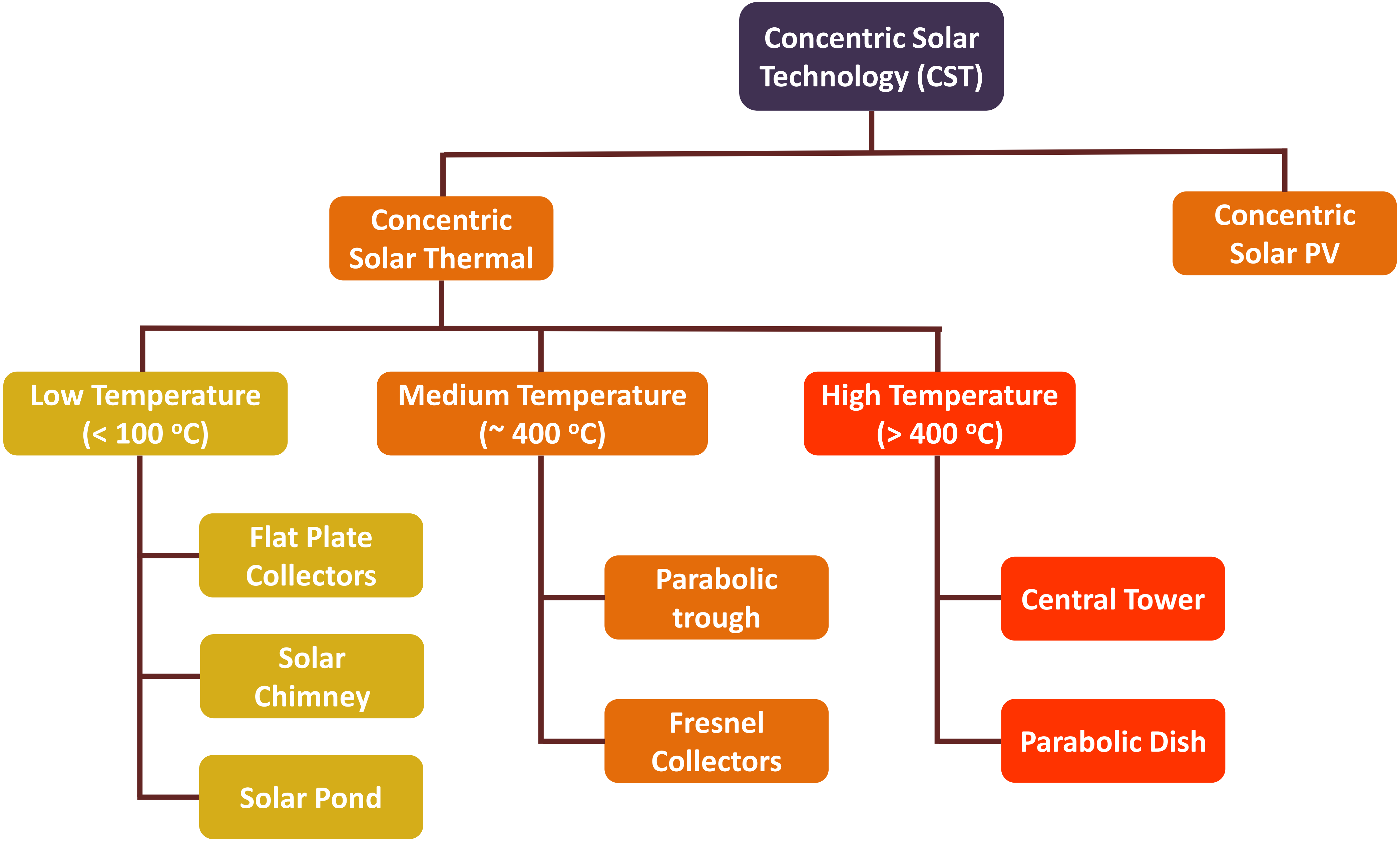
Schematic of Linear Fresnel Collector power plant

Stationary concentrating solar collectors

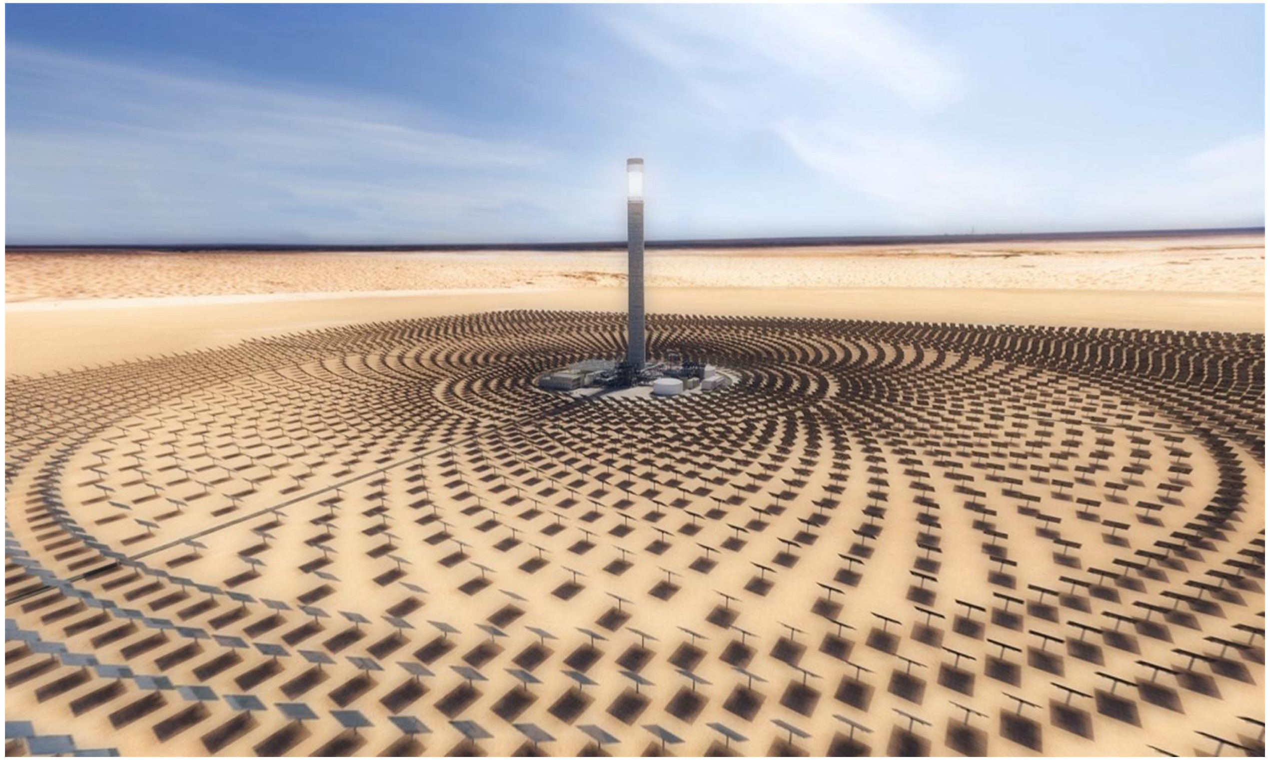
- ✓ Stationary concentrating collectors use compound parabolic reflectors and flat reflectors for directing solar energy to an accompanying absorber or aperture through a wide acceptance angle.
- ✓ The wide acceptance angle for these reflectors eliminates the need for a sun tracker.
- ✓ This class of collector includes parabolic trough flat plate collectors, flat plate collectors with parabolic boosting reflectors, and solar cooker.



Concentric Solar Technology (CST) for Power Generation

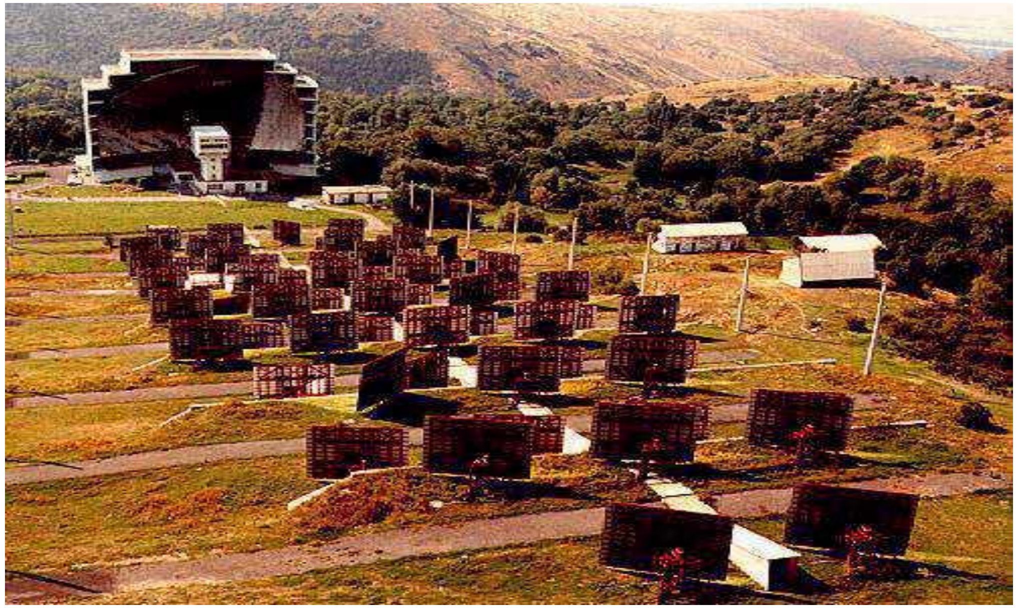


Schematic of parabolic trough power generation
Parabolic trough power plant



Power tower system with heliostats

Solar parabolic dish system



Solar furnace

Lens concentrators

Summary

- Working principle of differed concentrating collectors
- Comparison of concentrating collectors
  - Power towers and troughs are best suited for large, grid-connected power projects in the range of 30-200 MW
  - Dish/Engine systems are modular and can be used in single dish applications or grouped in dish farms to create larger multi-megawatt projects.
  - Parabolic trough plants are the most mature solar power technology available today and the technology most likely to be used for near future deployments.
  - Power towers, with low cost and efficient thermal storage, promise to offer dispatchable, high capacity factor, solar-only power plants in the near future.