16-CSP Technologies

ECEGR 4530

Renewable Energy Systems

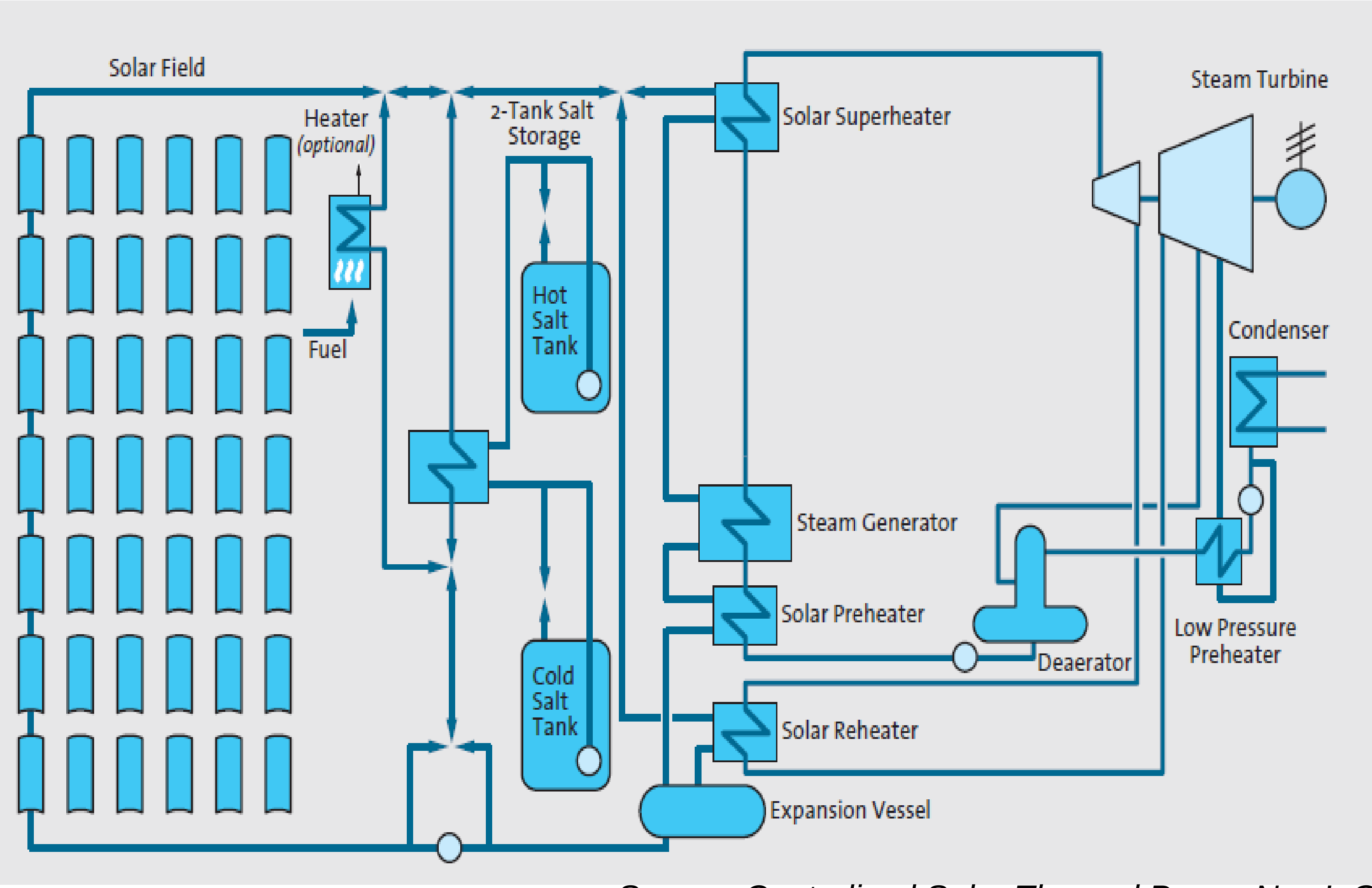
Overview

- State of the Industry
- Parabolic Trough Collector (PTC)
- Centralized Receiver Systems (solar towers)
- Dish
- Thermal Energy Storage
- Hybrid Systems

CSP Industry

- Installed capacity (4,400 MW) lags solar PV by large margin (227,000 MW)
  1. Spain: 2,300 MW
  2. U.S.: 1,634 MW
  3. India: 225 MW
  4. U.A.E.: 100 MW
- Installation rates growing rapidly (+925 MW in 2014)

PTC Technology Overview



Source: Centralized Solar Thermal Power Now!, Greenpeace

SEGS VIII and
SEGS IX, 80 MW each

(Photo courtesy of SkyFuel Inc.)

PTC Overview

- PTCs are the most mature CSP technology
- Notable CSP plants
  - SEGS II-IX (354 MW total)
  - Genesis Solar Energy Project (250 MW)
  - Nevada Solar One (64-70MW)
- Efficiency gains can still occur
- Concentration ratios: 30-80
- Sizes: 30 – 80MW
- Best land use factor of all CSPs

Nevada Solar One Video

https://www.youtube.com/watch?v=tNFfmHzuqP4

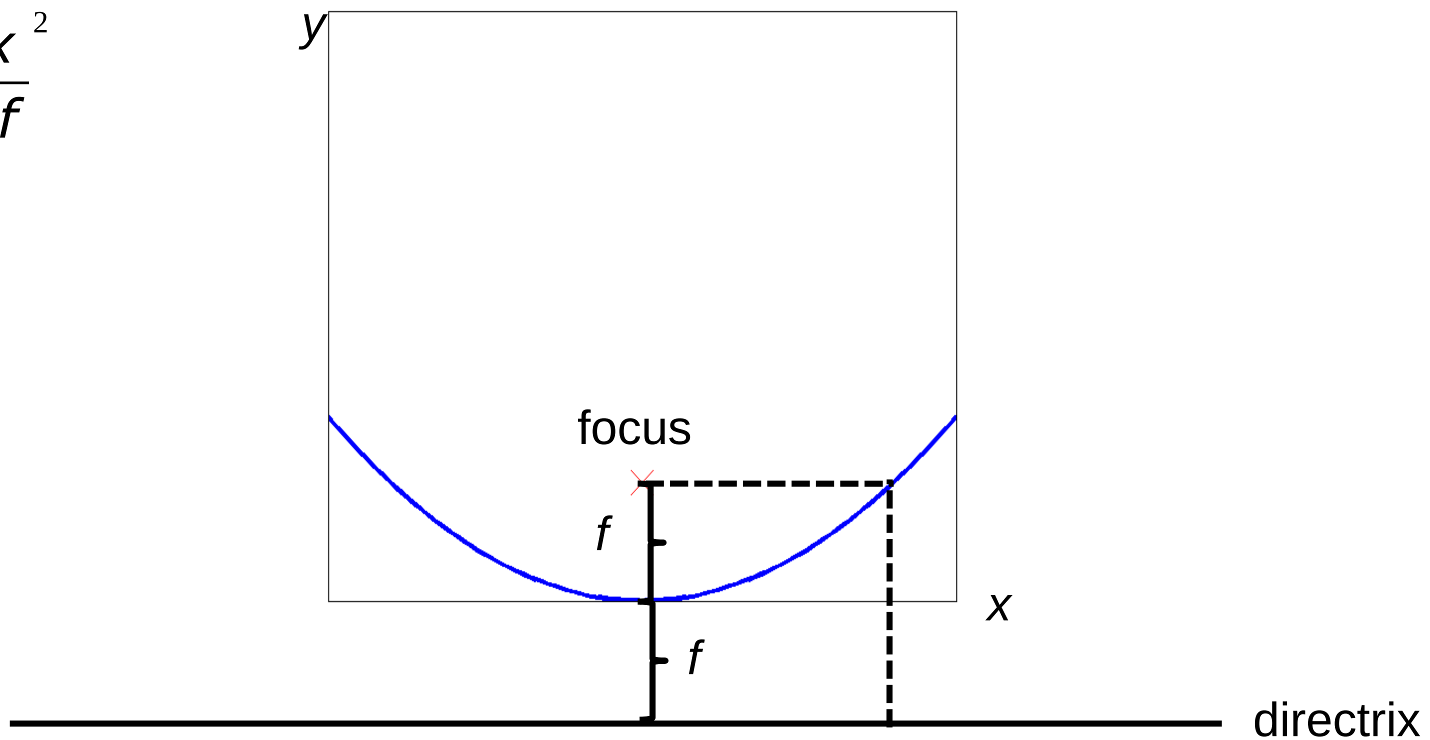
PTC Costs

- Electrical energy cost: \$0.12-0.15/kWh
- Capital costs: \$2,400 – 3,500/kW
- Operations and maintenance: \$0.01 – 0.023/kWh

PTC Collector

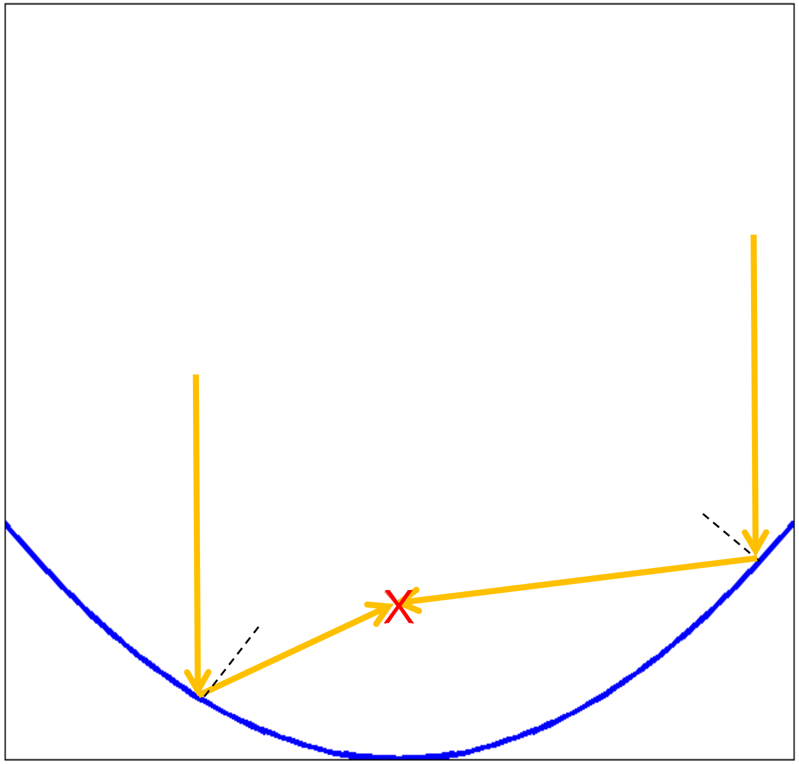
- Parabola: set of points on a plane that are equidistant from a point (the focus) and a line (directrix)

$$y = \frac{x^2}{4f}$$



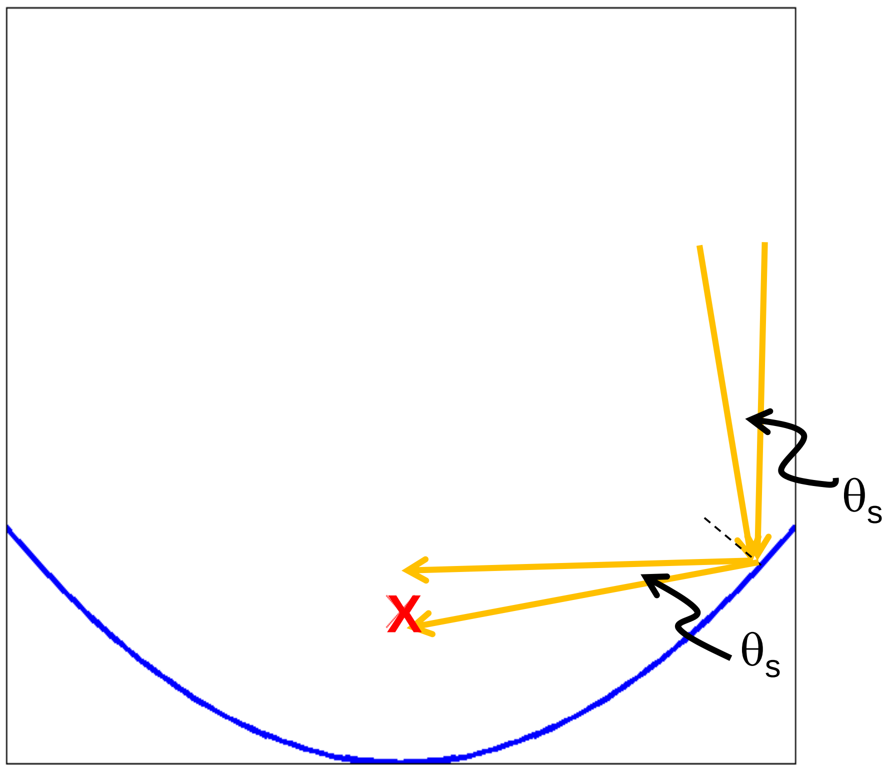
PTC Collector

- All lines parallel to the axis of symmetry will reflect to the focus



PTC Collector

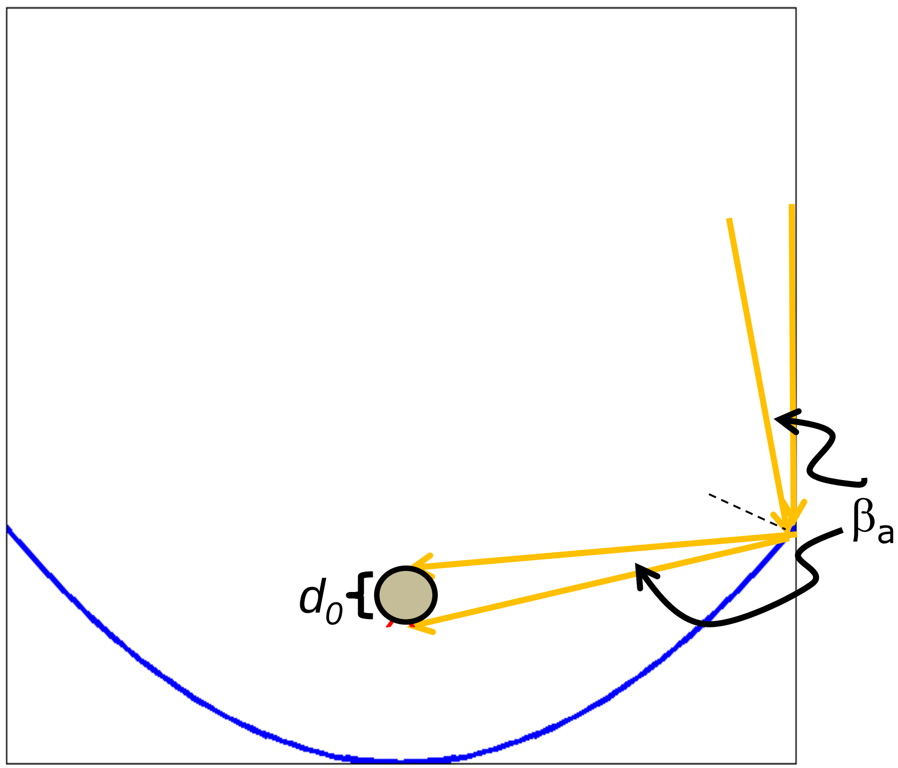
- Recall that the solid angle subtended by the Sun is 0.53° (rays are not all parallel)
- Receiver cannot be a point



exaggerated angle shown

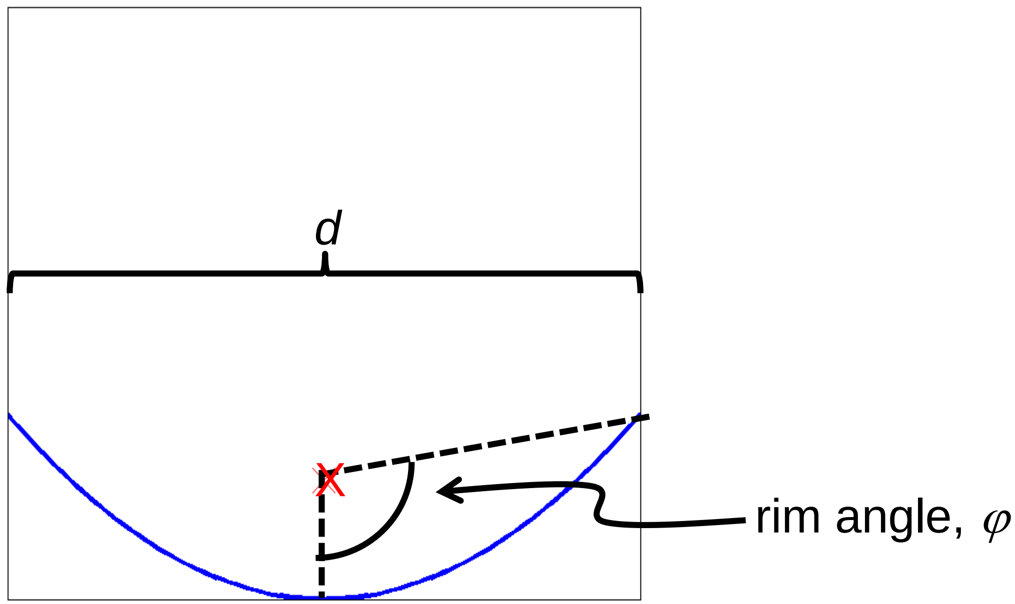
PTC Collector

- Design for an acceptance angle β_a around 1° to 2°
- Less precise tracking of Sun needed



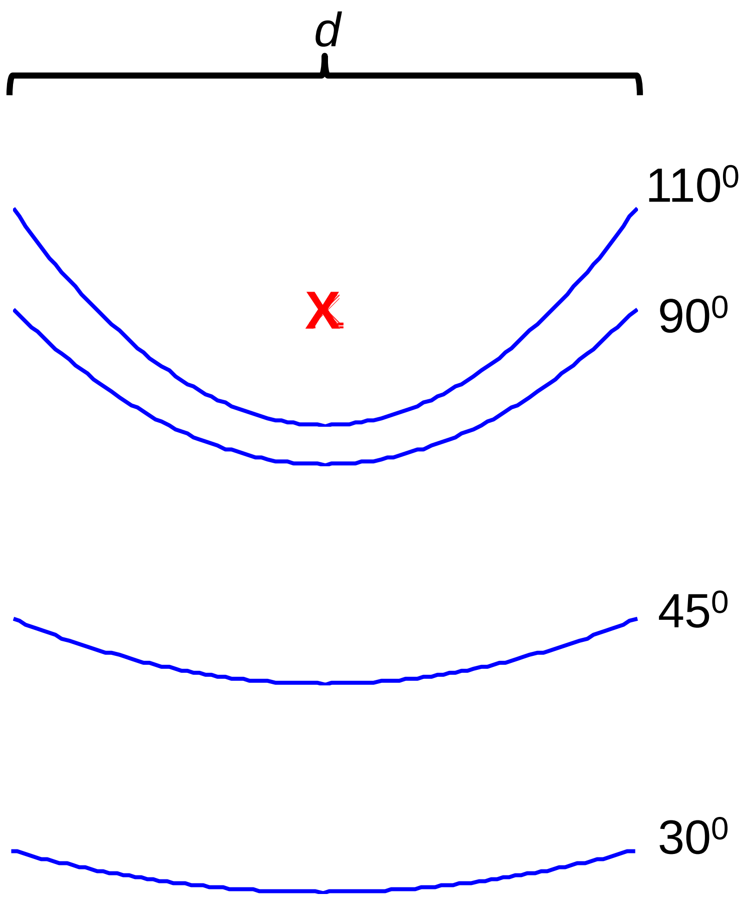
PTC Collector

- Truncated parabola described by:
  - rim angle, φ
  - width, d
  - focus distance, f



PTC Collector

- As rim angle increases, focal distance decreases
- PTCs: $70^o < \varphi < 110^o$



Geometric Relationships

$$y = \frac{x^2}{4f} \quad \text{(eqn of a parabola)}$$

$$y = \frac{d^2}{16f}$$

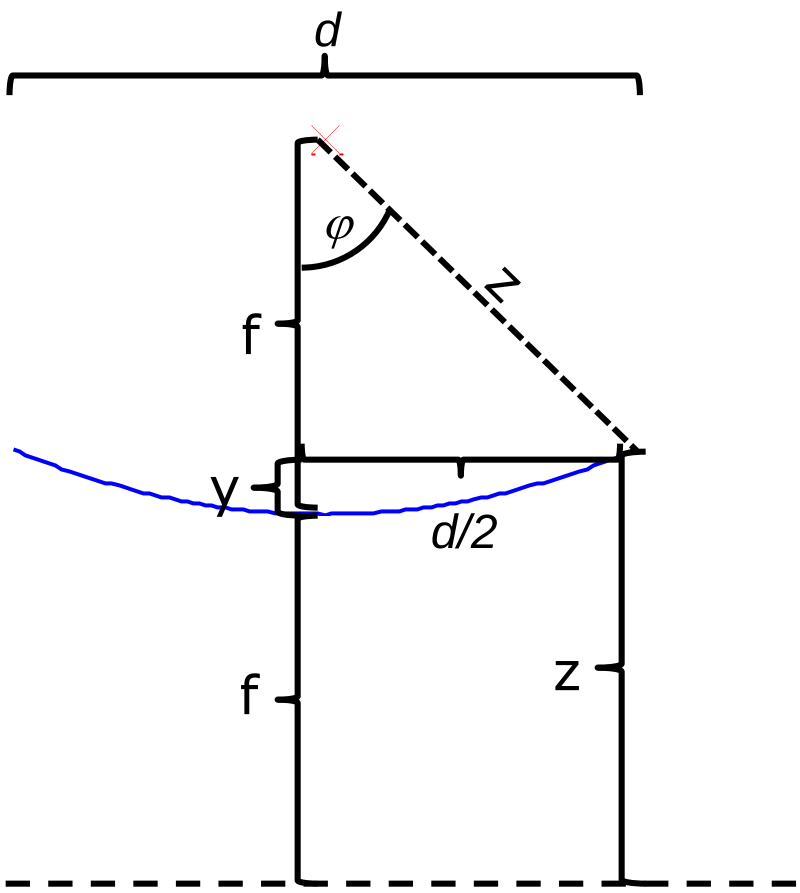
$$z\sin\varphi = d/2$$

$$z\cos\varphi = f - y$$

Half tangent formula

$$\tan\left(\frac{\varphi}{2}\right) = \frac{\sin\varphi}{1+\cos\varphi} = \frac{\frac{d/2}{z}}{1+\frac{f-\frac{d^2}{16f}}{z}} = \frac{d/2}{z+f-\frac{d^2}{16f}}$$

$$\tan\left(\frac{\varphi}{2}\right) = \frac{d/2}{f+\frac{d^2}{16f}+f-\frac{d^2}{16f}} = \frac{d}{4f}$$



PTC Collector

- Geometric relationships

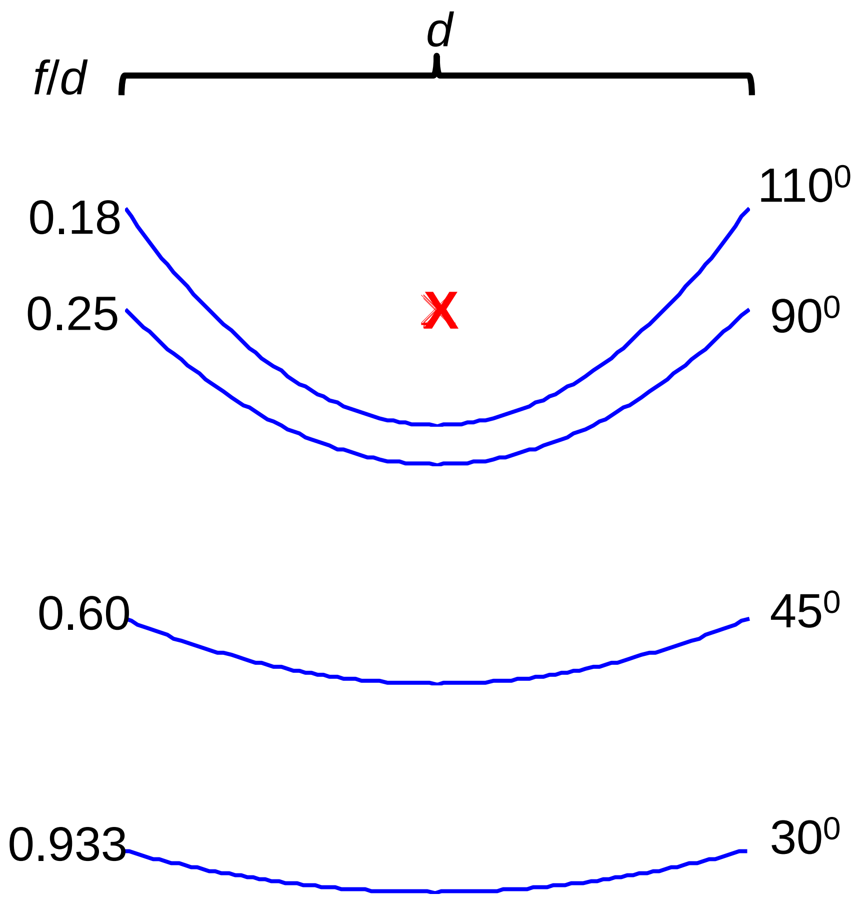
$$\frac{d}{4f} = \tan\left(\frac{\varphi}{2}\right)$$

$$\frac{f}{d} = \frac{1}{4\tan\left(\frac{\varphi}{2}\right)}$$ Focal length/diameter relationship

$$C = \frac{\ell d}{\pi d_o \ell} = \frac{d}{\pi d_o}$$ concentration ratio

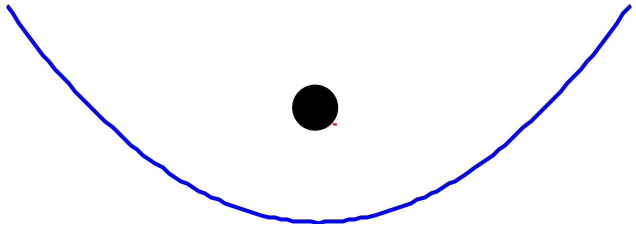
ℓ : length of trough

Approximation since not all of the receiver area is used



Geometric Relationships

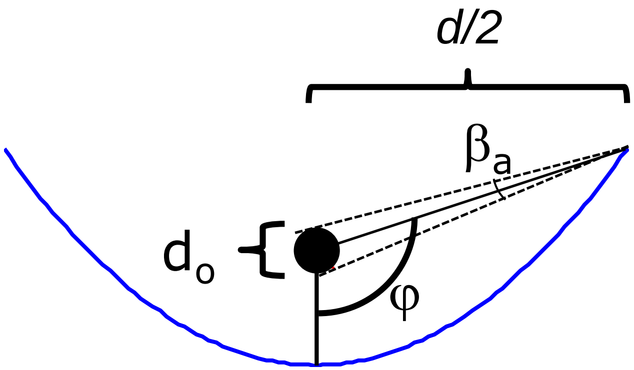
- Consider a 4.75 m wide parabolic trough with φ = 110° and β_a = 1°. Find the concentration ratio



Geometric Relationships

- Need to use: $C = \dfrac{d}{\pi d_o}$

- We must solve for d_o using geometry

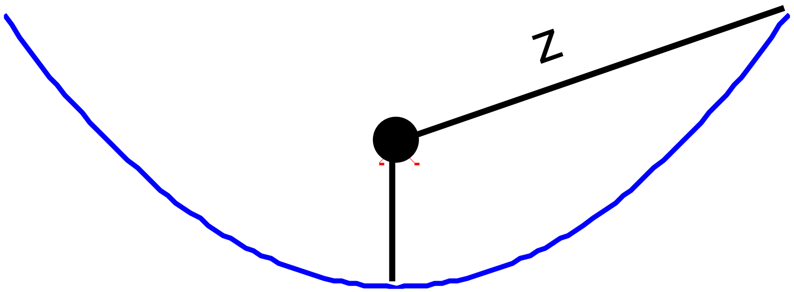


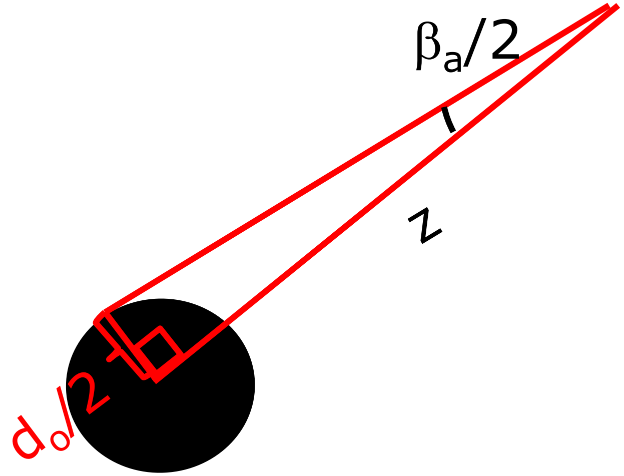
Geometric Relationships

- Solving

$$z = \frac{d/2}{\sin\varphi} = 2.53\ \text{m}$$

$$d_0 = 2z\tan\frac{\beta_a}{2} = 0.044\ \text{m}$$





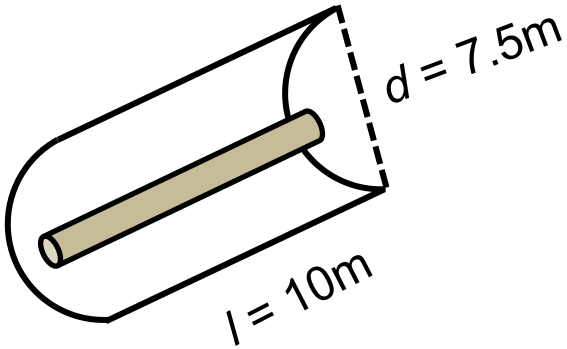
Geometric Relationships

- Solving for the concentration ratio

$$C = \frac{d}{\pi d_o} = 35.9$$

Example

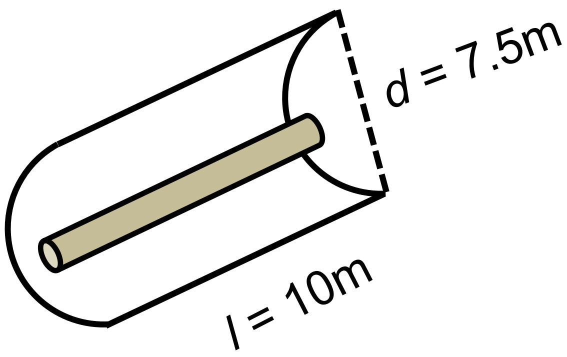
- Find the concentration ratio of the shown PTC if the rim angle is 100 degrees and the diameter of the receiver is 0.05m.



Example

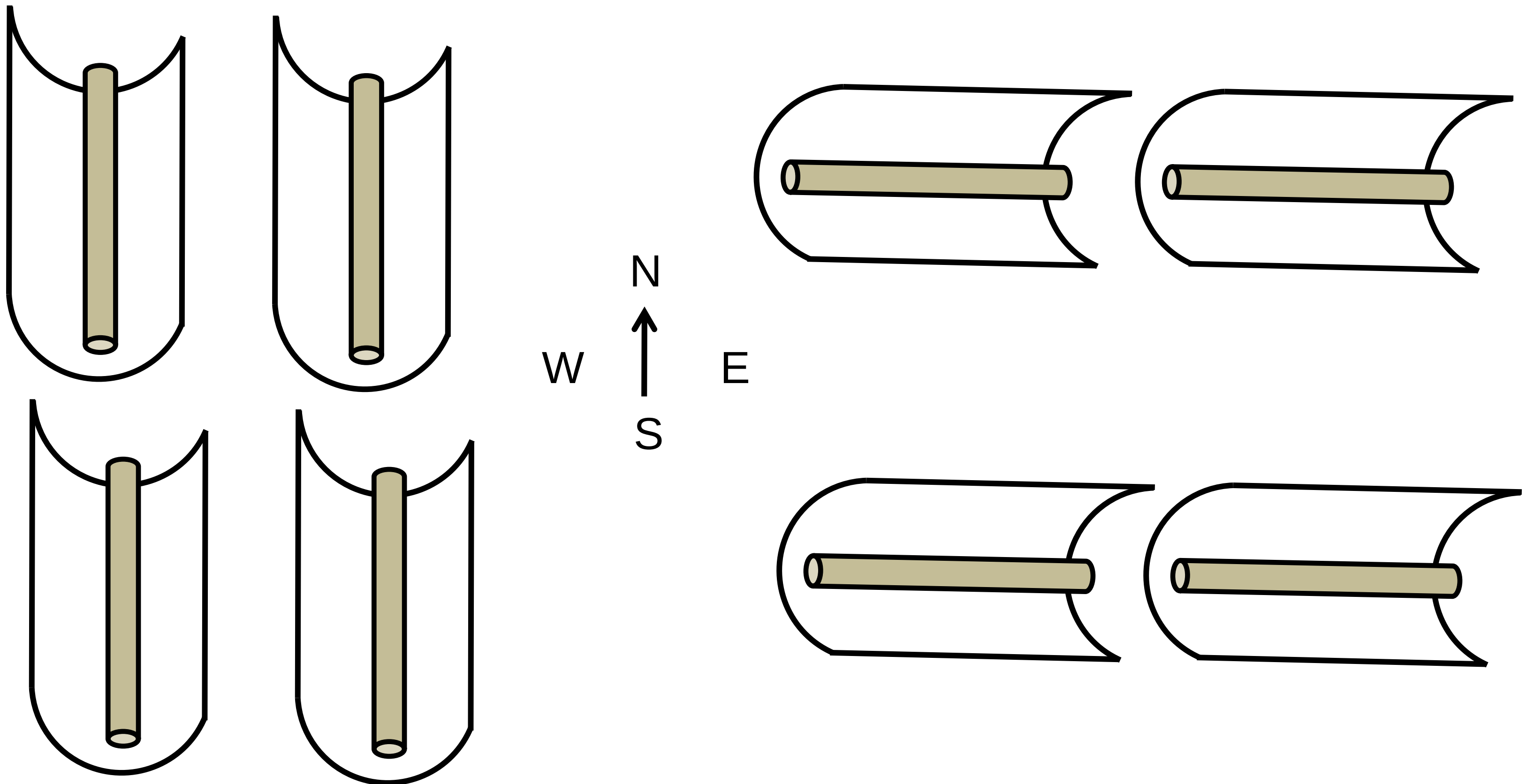
- Find the concentration ratio of the shown PTC if the rim angle is 100 degrees and the diameter of the receiver is 0.05m.

$$C = \frac{d}{\pi d_o} = \frac{7.5}{\pi(0.05)} = 47.75$$



Orientation

- Which way should the troughs be oriented?



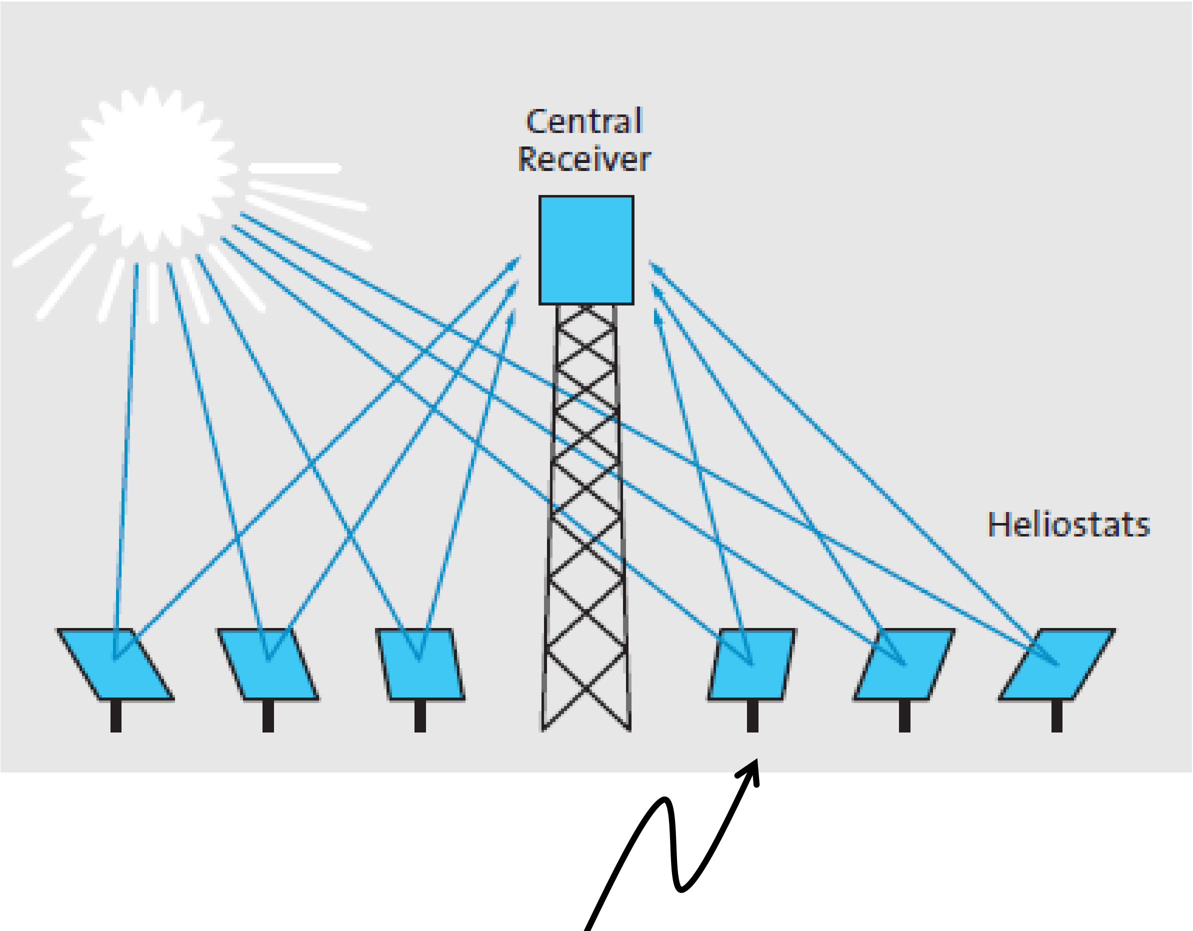
Orientation

- Collector orientation influences incidence angle of the Sun
- North-South layout: large seasonal variation (3-4 times is possible), greater overall energy production
- East-West layout: even distribution of energy production
- Select orientation for specific conditions (energy prices, load, etc)

PTC

- Troughs rotate on one axis to track the Sun
- Receiver is a tube composed of an inner pipe (carrying the working fluid) surrounded by a vacuum
- Working fluid temperature range: 150-400 ^{o}C
  - usually an oil (water use would result in high pressure at the operating temperature
- Steam turbine is used (due to the low temperature)

Solar Tower Technology Overview



heliostats arranged like a large paraboloid

Source: Centralized Solar Thermal Power Now!, Greenpeace

Solar Tower Technology Overview

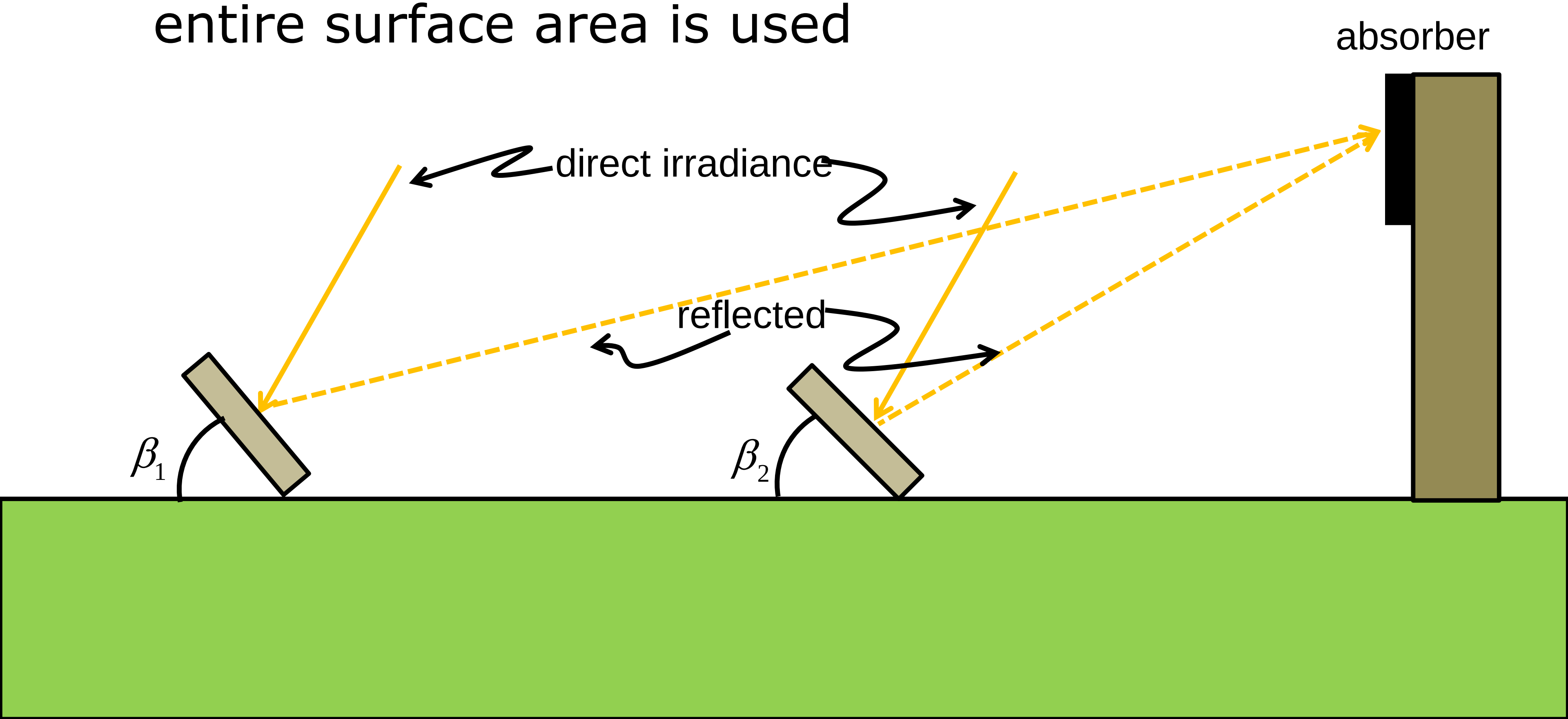
(Photo courtesy of Sandia National Laboratories)

Solar Tower Overview

- Research-scale plants built in the 1980s
- First commercial plants built in Spain (2007), approximately 11 MW (for now)
  - 624 mirrors
- Efficiency gains can still occur
- Concentration ratio: 500-1000
- Large land use

Solar Tower Overview

- Heliostats rotate on two axes
  - each has different angles
  - complex control
- Heliostat surface is not normal to the Sun, so not entire surface area is used



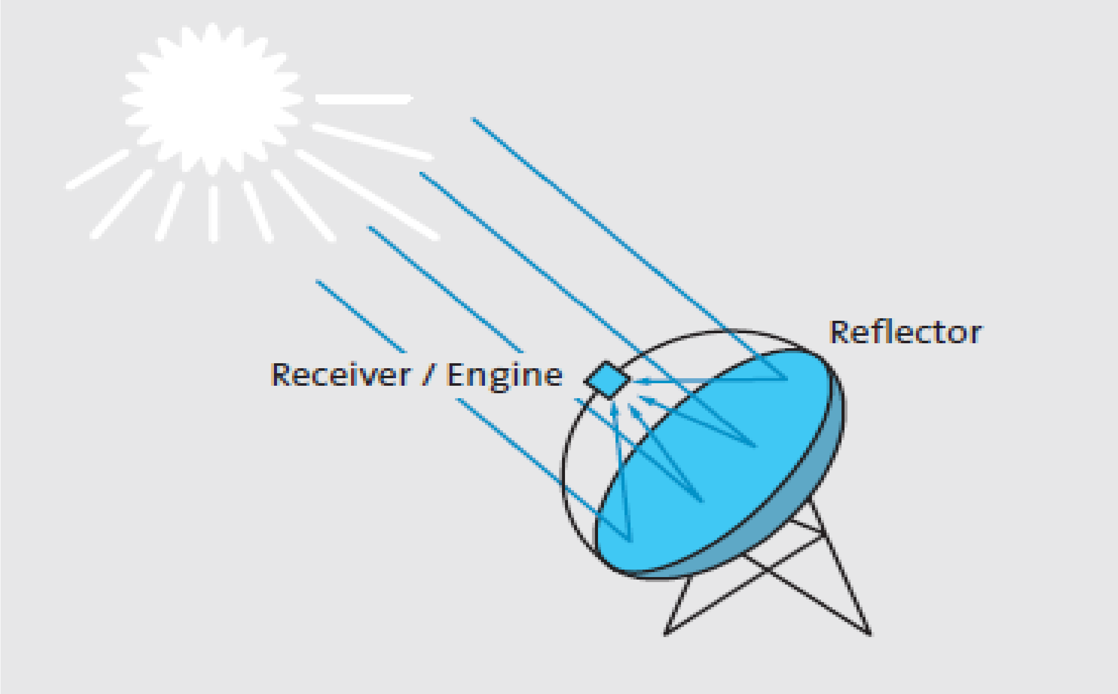
Solar Tower Overview

- Capable for high temperature operation (800 ^{o}C):
  - hydrogen production or combustion turbine operation
  - efficient thermal storage (claimed to decrease overall cost of energy if included)
  - integration into fossil fuel plants

Solar Tower Costs

- Electrical energy cost: €0.14-0.20/kWh
  - expected to drop to €0.05/kWh
- Capital costs: €2,700/kW (with storage)

Parabolic Dish Overview



Source: Centralized Solar Thermal Power Now!, Greenpeace

(Photo courtesy of Sandia National Laboratories/Randy Montoya)

Parabolic Dish Overview

- Modular (mechanical limitations on dish size)
- 5 to 50kW
- Current applications in distributed, off-grid applications
- Large plants planned (500 MW)
- High efficiency: 30% solar-to-electric possible
- Temperatures around 700 ^{o}C
- Two-axis tracking
- Highest concentration ratios (1000+)

Parabolic Dish Costs

- Electrical energy cost: € 0.15/kWh
- Capital costs: €10,000 – 14,000/kW
  - could drop to €7,000/kW in the short term
  - target: €1,600/kW

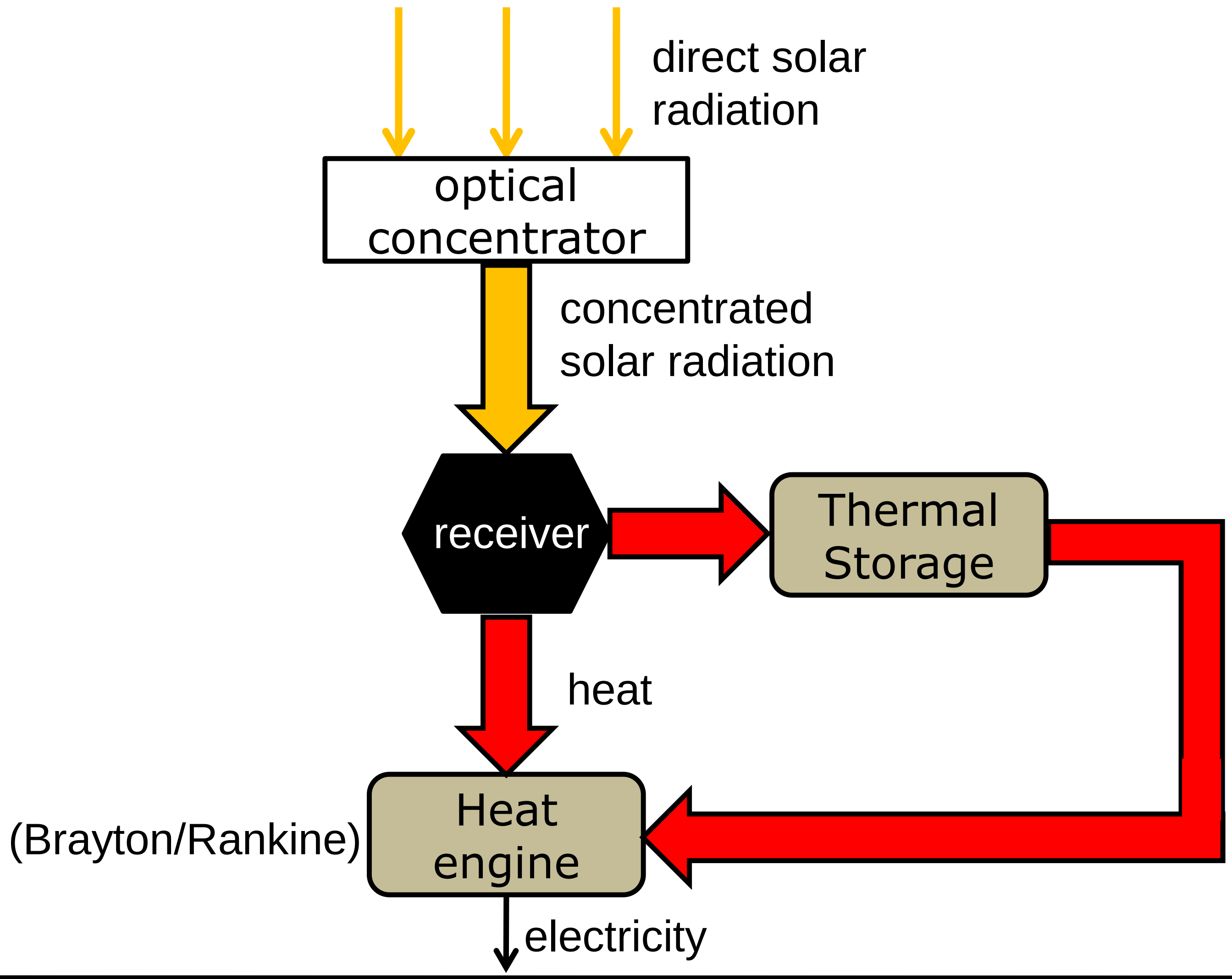
Comparison

Technology	Peak Efficiency (%)	Annual Efficiency (%)
Trough	21	10-12 up to 14-18
Power Tower	23	14-19
Dish	29	18-23

	Parabolic Trough	**Central Receiver**	**Parabolic Dish**
Applications	Grid-connected plants, mid- to high process heat (80MWe)	Grid-connected plants, high temperature process heat (10MWe)	Stand-alone, small off-grid power systems or clustered to larger grid connected dish parks (25 kwe size)
Advantages	• Commercially available operating temperature potential up to 500°C • Commercially proven annual net plant efficiency of 14% • Commercially proven investment and operating costs • Modularity • Best land-use factor of all solar technologies • Lowest materials demand • Hybrid concept proven • Storage capability	• Good mid-term prospects for high conversion efficiencies, operating temperature potential beyond 1,000°C • Storage at high temperatures • Hybrid operation possible	• Very high conversion efficiencies – peak solar to net electric conversion over 30% • Modularity • Hybrid operation possible • Operational experience of first demonstration projects
Disadvantages	The use of oil-based heat transfer media restricts operating temperatures today to 400°C, resulting in only moderate steam Qualities	Projected annual performance values, investment and operating costs still need to be proven in commercial operation	Reliability needs to be improved • Projected cost goals of mass production still need to be achieved

Source: Centralized Solar Thermal Power Now!, Greenpeace

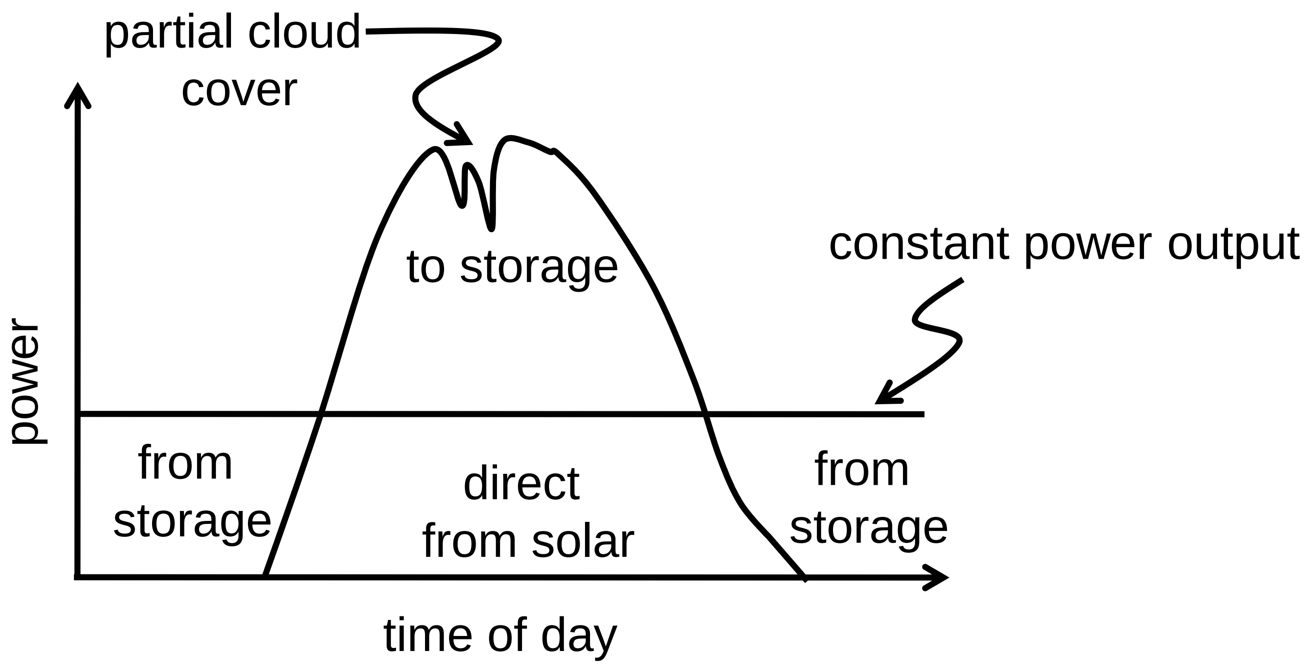
Thermal Storage



Thermal Storage

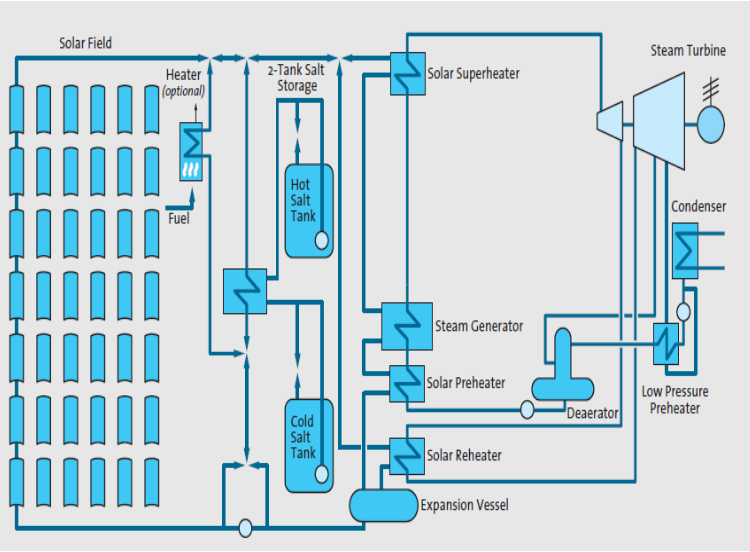
- Thermal energy at high temperature can be efficiently stored (95%)
- Allows for greater control (dispatchability) of the electrical power output of the CSP plant
- Reduces need for large generator size
- Low cost: $25-75/kWh
- Thermal nature of CSP provides an inertia that buffers against transient changes in DNI (cloud cover) even without a discrete storage module

Thermal Storage

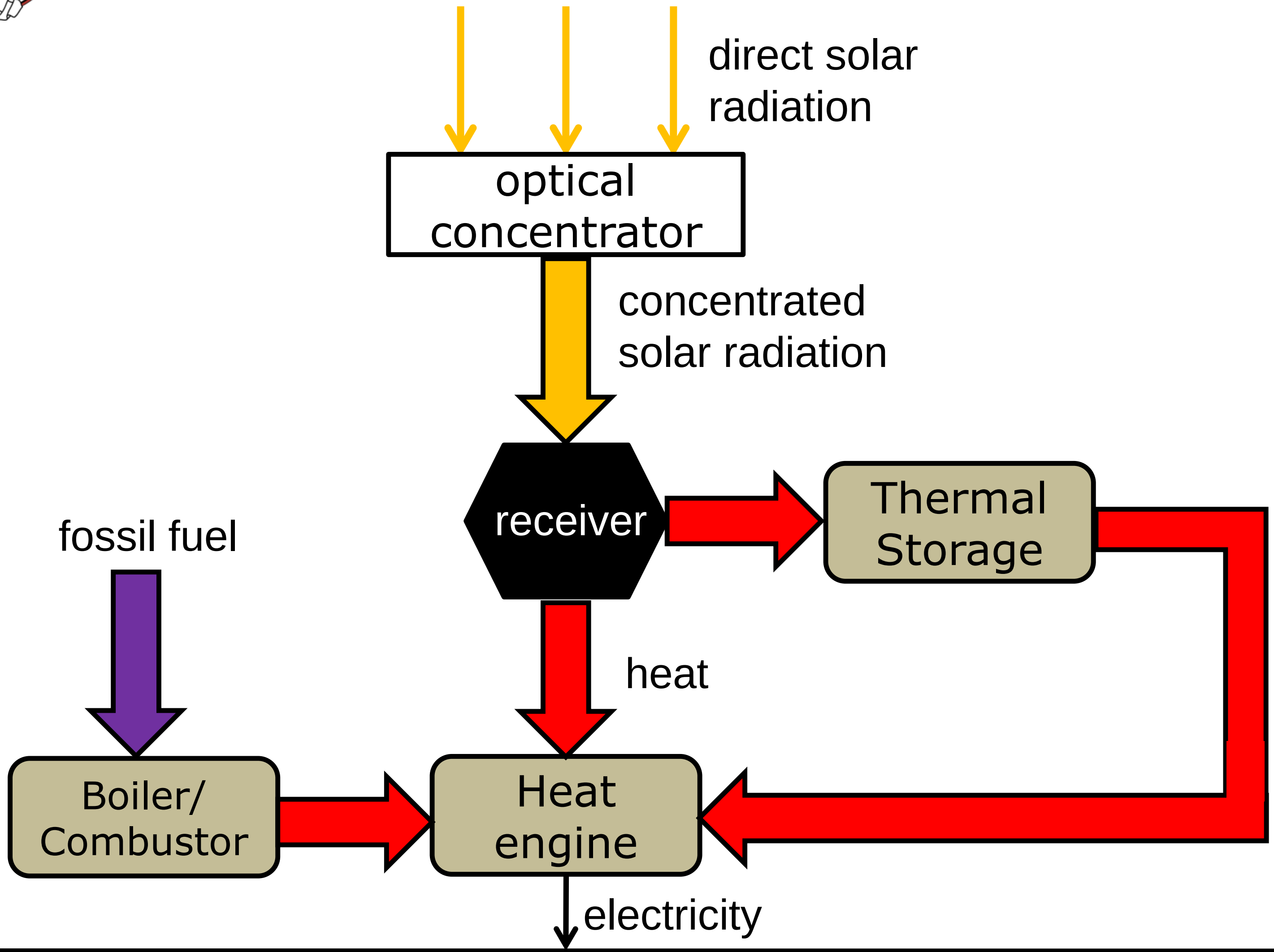


Thermal Storage

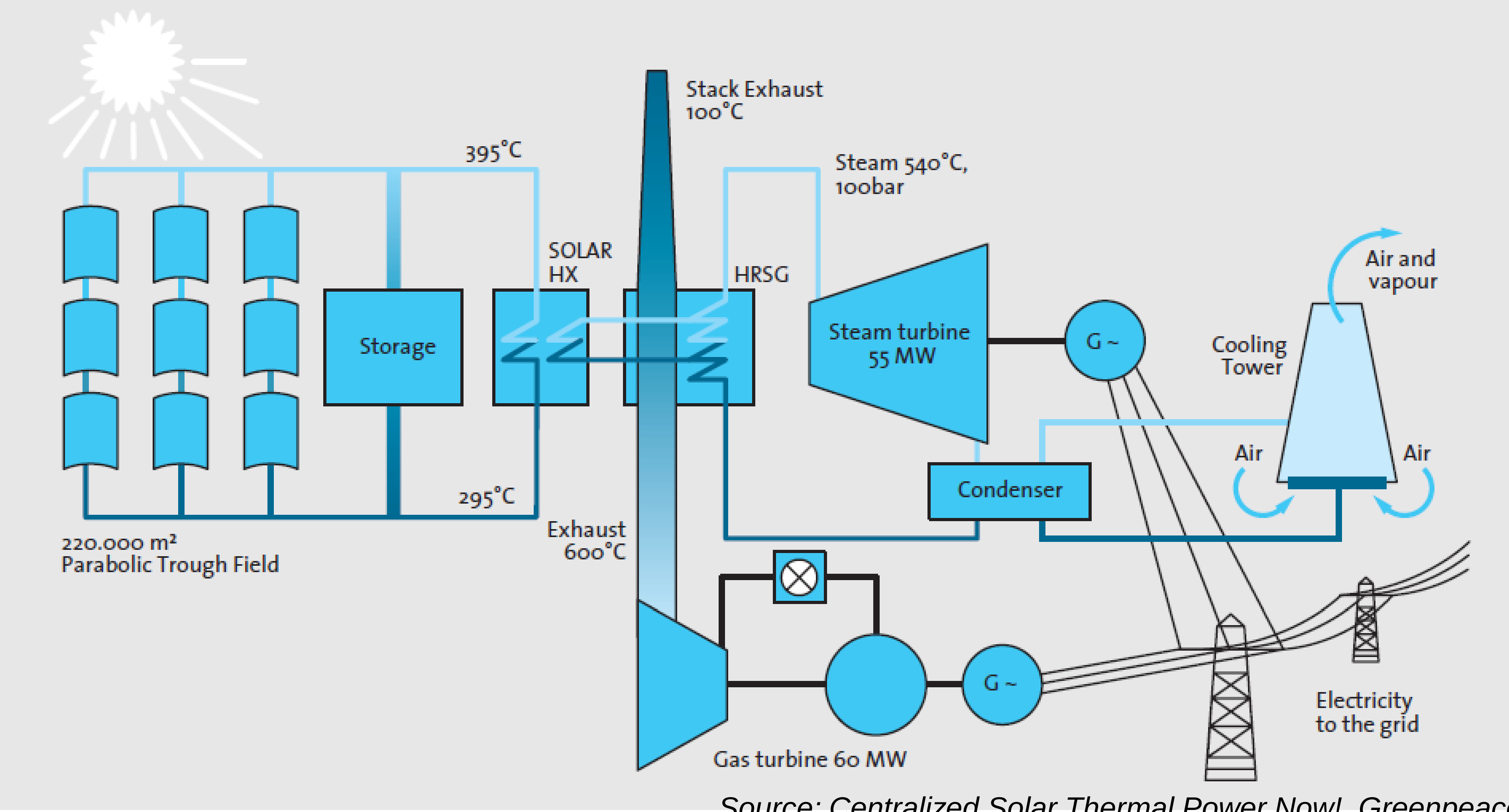
- Two designs:
  - single-medium storage: working fluid is the same as the storage medium
  - dual-medium storage: storage medium can be iron plates, molten salt, concrete



Hybrid


direct solar
radiation
optical
concentrator
concentrated
solar radiation
receiver
Thermal
Storage
fossil fuel
heat
Boiler/
Combustor
Heat
engine
electricity

Integrated Solar Combined Cycle (ISCC)



Source: Centralized Solar Thermal Power Now!, Greenpeace

Key Requirements for Solar Thermal

- Clear, cloud-free location (high DNI)
- Access to water supply
- Contiguous area of land (for large collector fields)
- Access to uncongested transmission lines

Reading

- Solar Energy Industry Association, Concentrating Solar Power Fact Sheet (on Canvas)