

# 20-CSP Technologies

ECEGR 452

Renewable Energy Systems

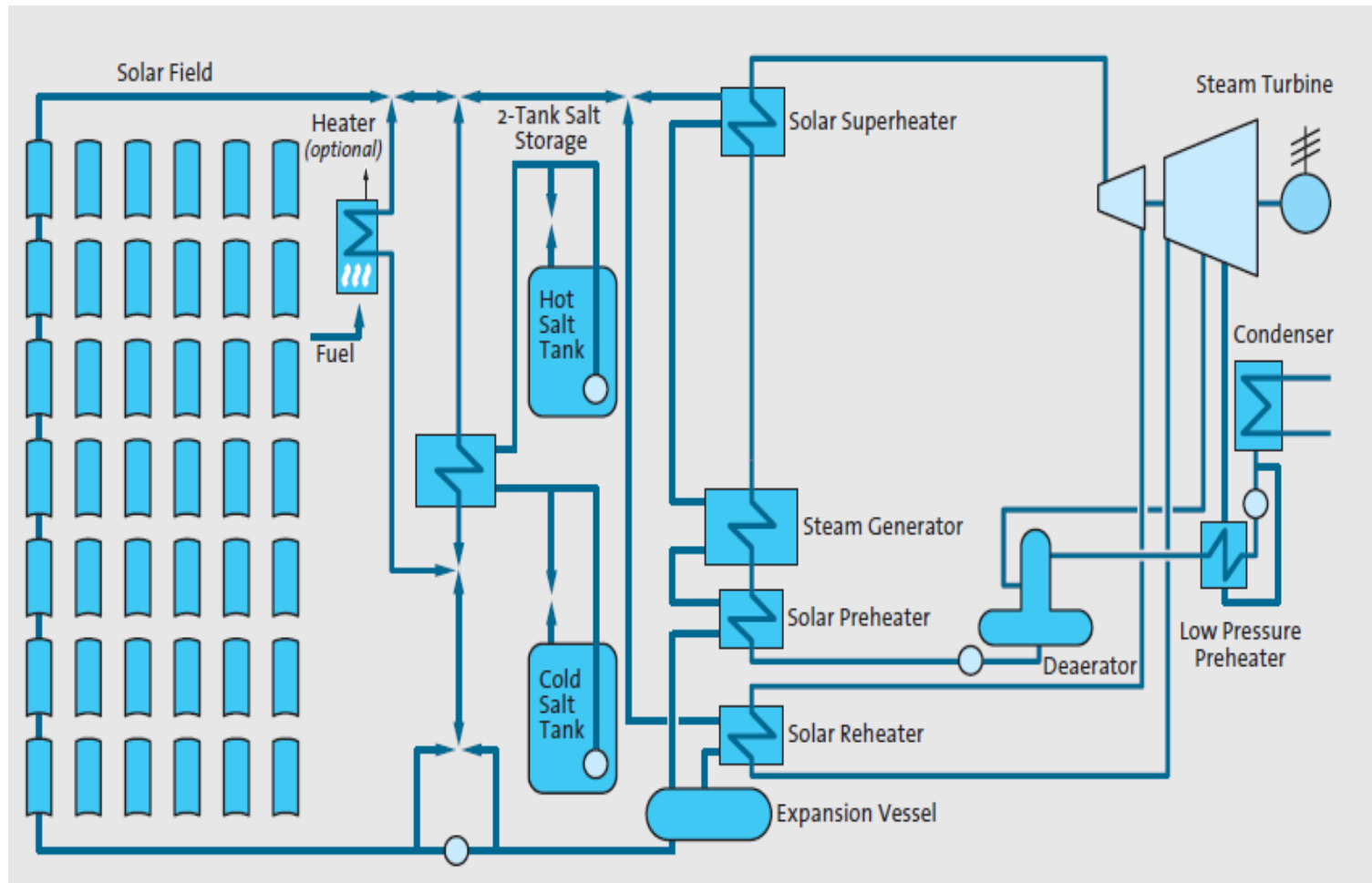


# Overview

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



# PTC Technology Overview



Source: *Centralized Solar Thermal Power Now!*, Greenpeace



SEGS VIII and  
SEGS IX, 80 MW each



1.46 miles



# 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

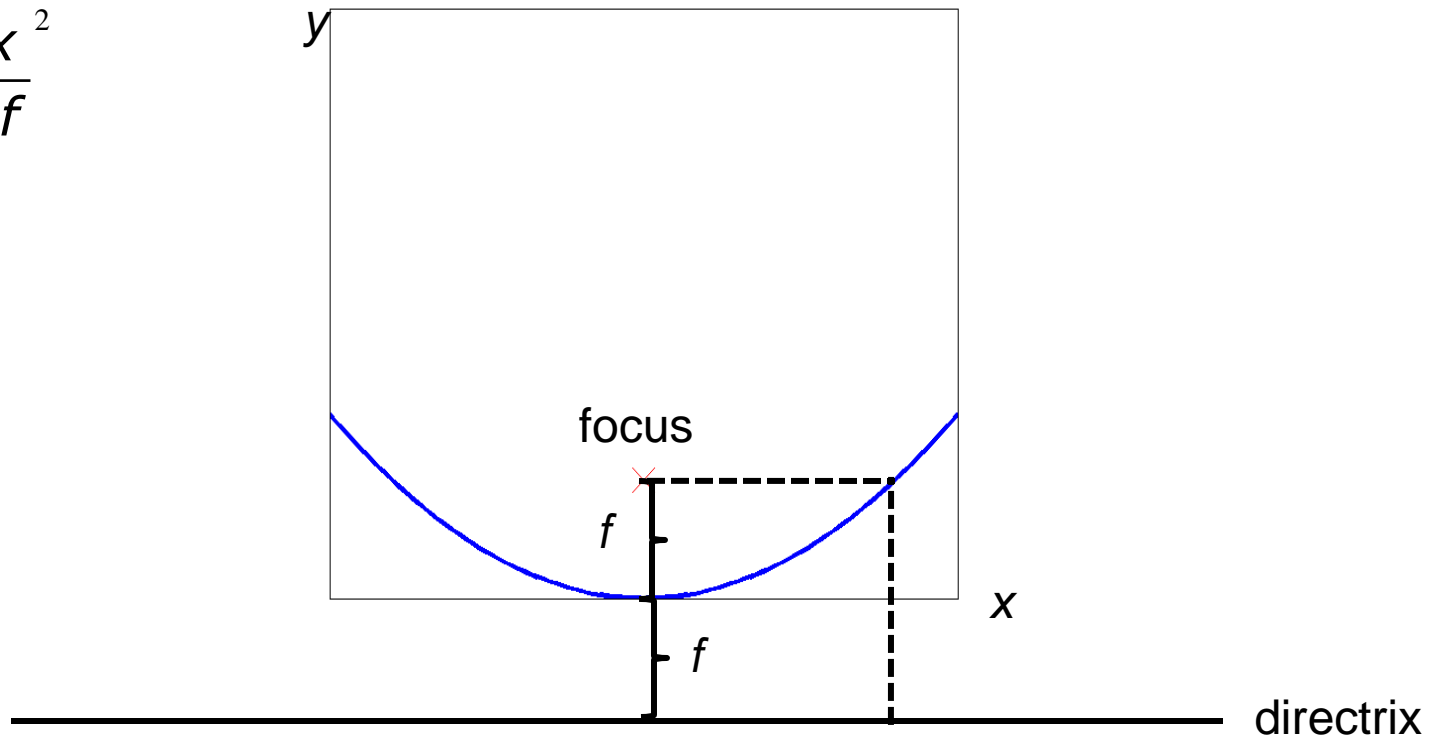
- Electrical energy cost: \$0.12-0.15/kWh
- Capital costs: \$2,400 – 3,500/kW
- Operations and maintenance: \$0.01 – 0.023/kWh



# PTC Collector

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

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

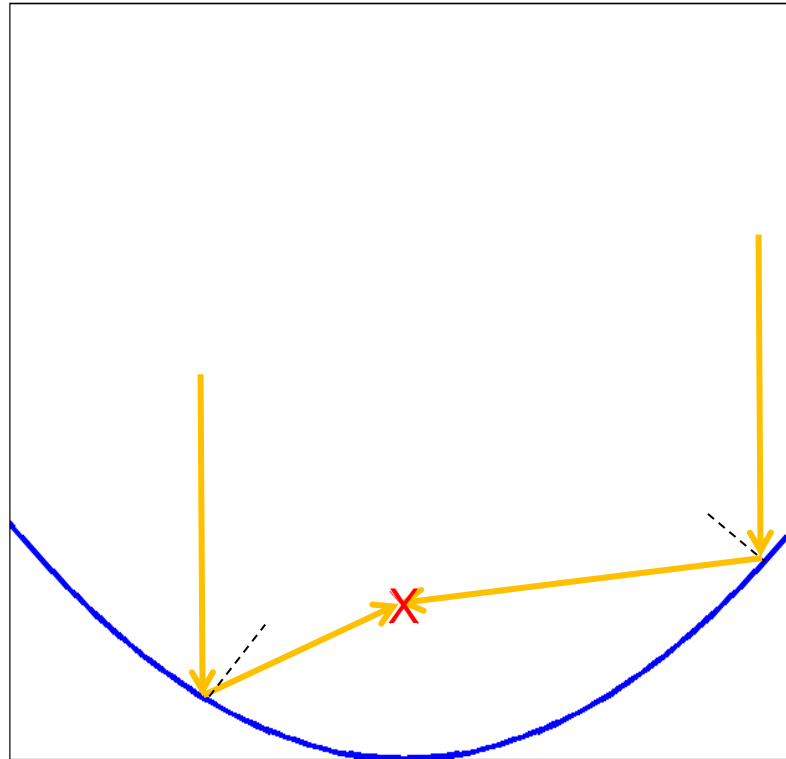






# PTC Collector

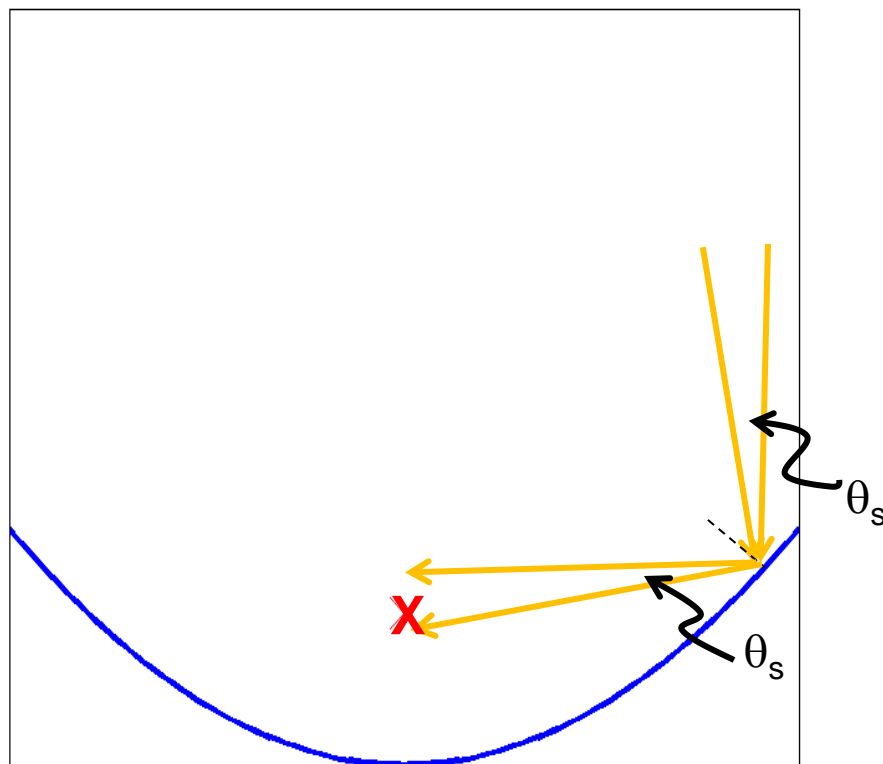
- All lines parallel to the axis of symmetry will reflect to the focus





# PTC Collector

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

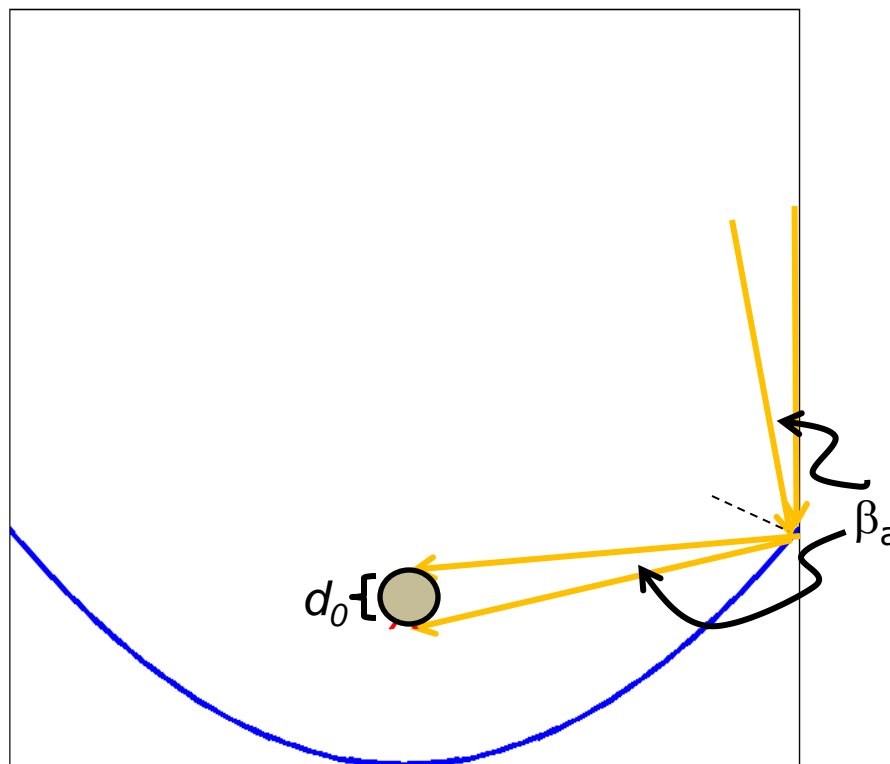


exaggerated angle shown



# PTC Collector

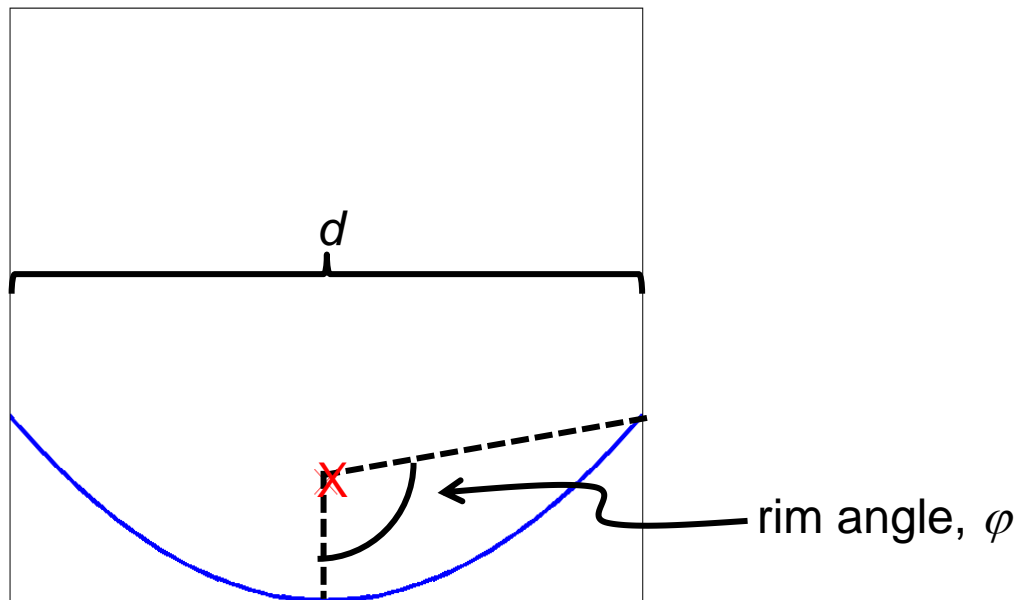
- Design for an acceptance angle  $\beta_a$  around  $1^\circ$  to  $2^\circ$
- Less precise tracking of Sun needed





# PTC Collector

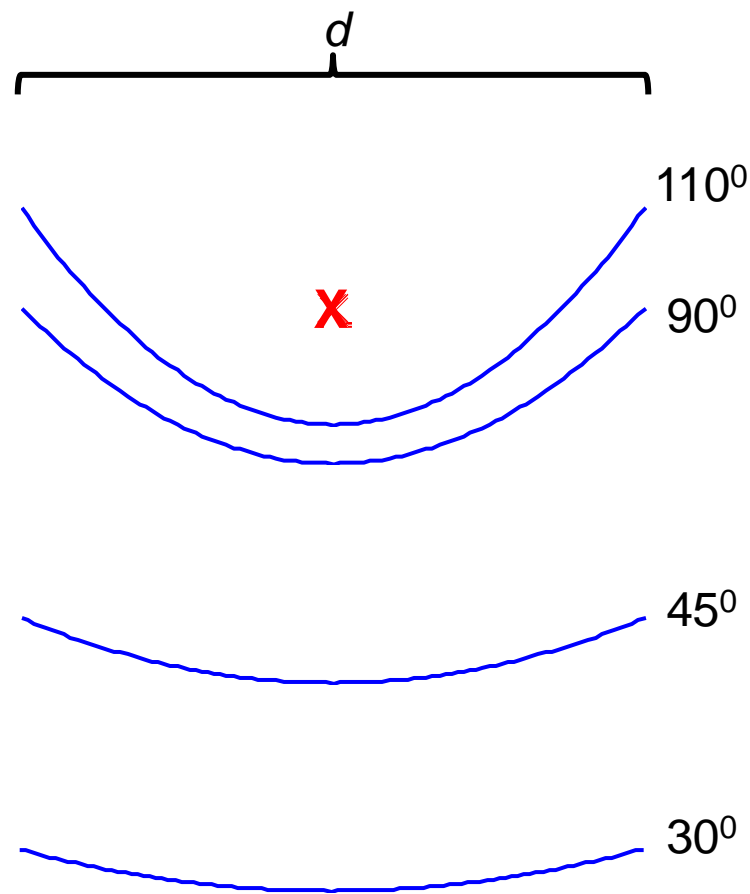
- Truncated parabola described by:
  - rim angle,  $\varphi$
  - width,  $d$
  - focus distance,  $f$





# PTC Collector

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





# Geometric Relationships

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

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

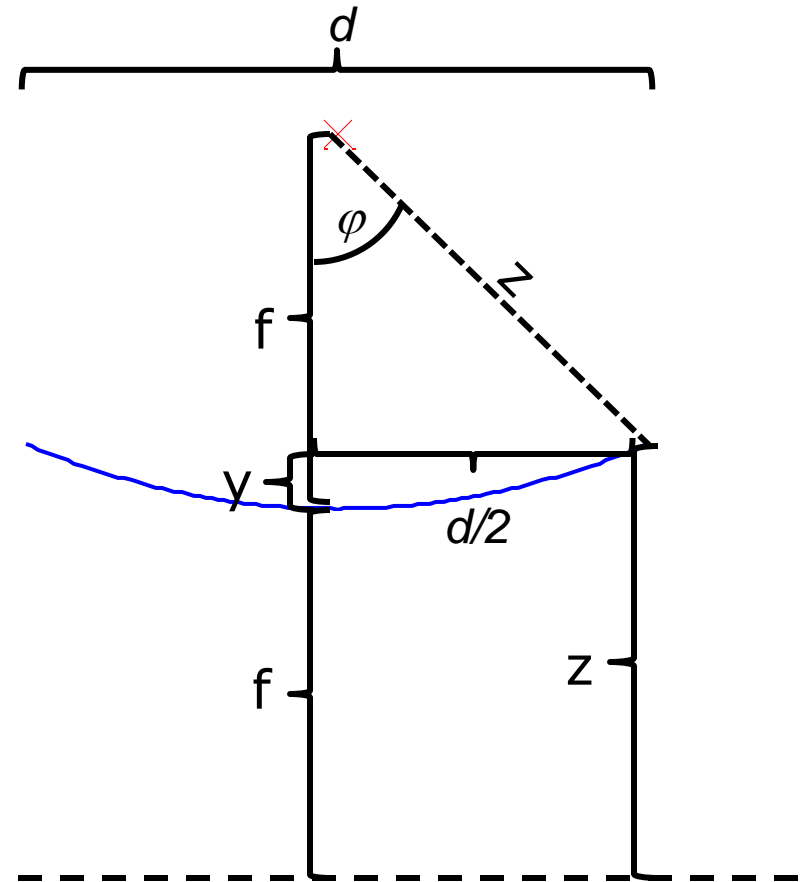
$$z \sin \varphi = \frac{d}{2}$$

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

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

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

$$\frac{f}{d} = \frac{1}{4 \tan\left(\frac{\varphi}{2}\right)}$$

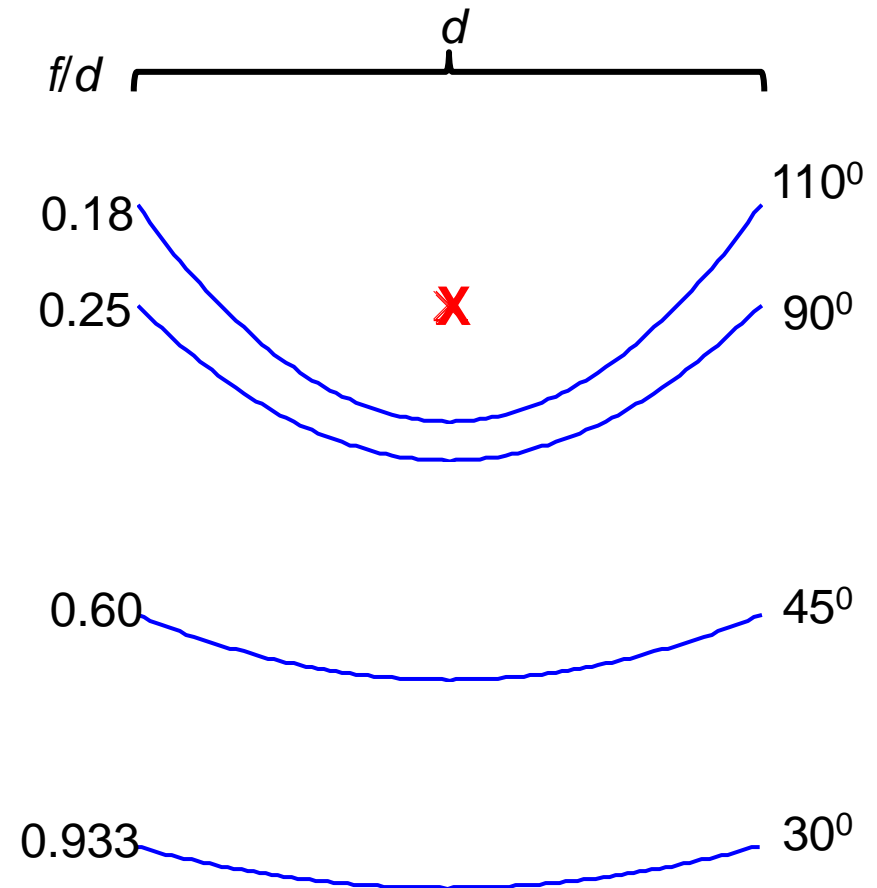
Focal length/diameter relationship

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

concentration ratio

$\ell$  : length of trough

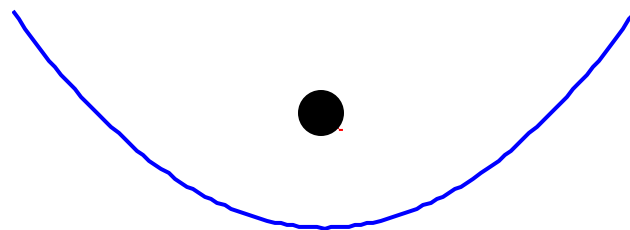
Approximation since not all of the receiver area is used





# Geometric Relationships

- Consider a 4.75 m wide parabolic trough with  $\varphi = 110^\circ$  and  $\beta_a = 1^\circ$ . Find the concentration ratio

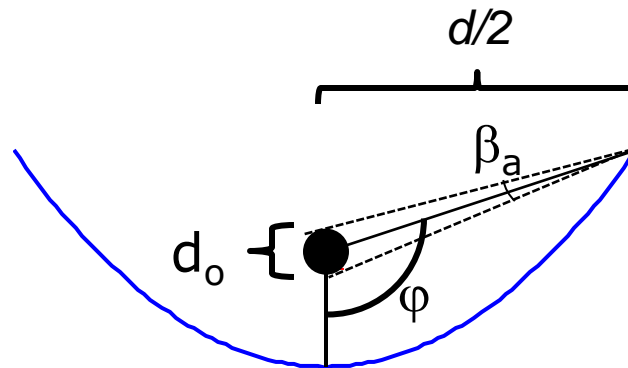






# Geometric Relationships

- Need to use:  $C = \frac{d}{\pi d_o}$
- We must solve for  $d_o$  using geometry



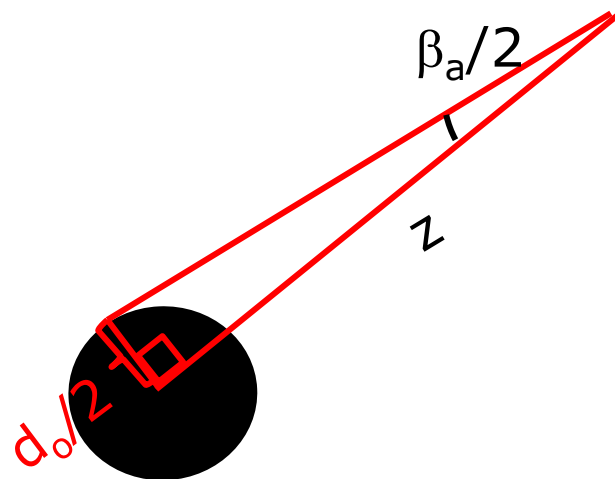
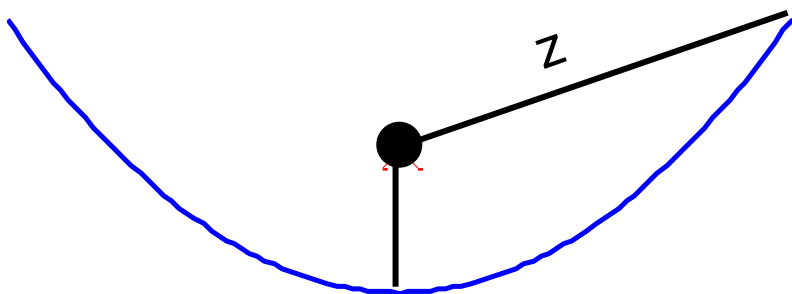


# Geometric Relationships

- 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

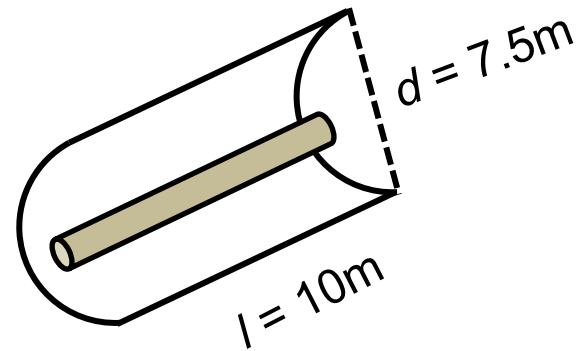
- Solving for the concentration ratio

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



# 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.

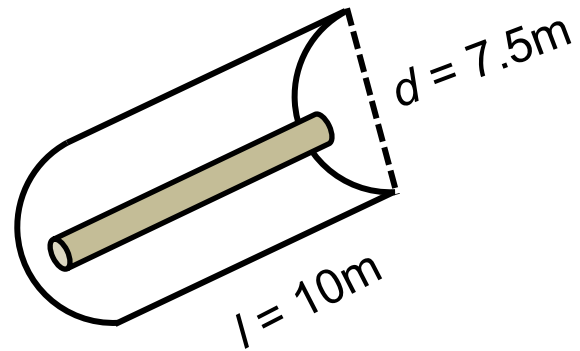




## Example

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

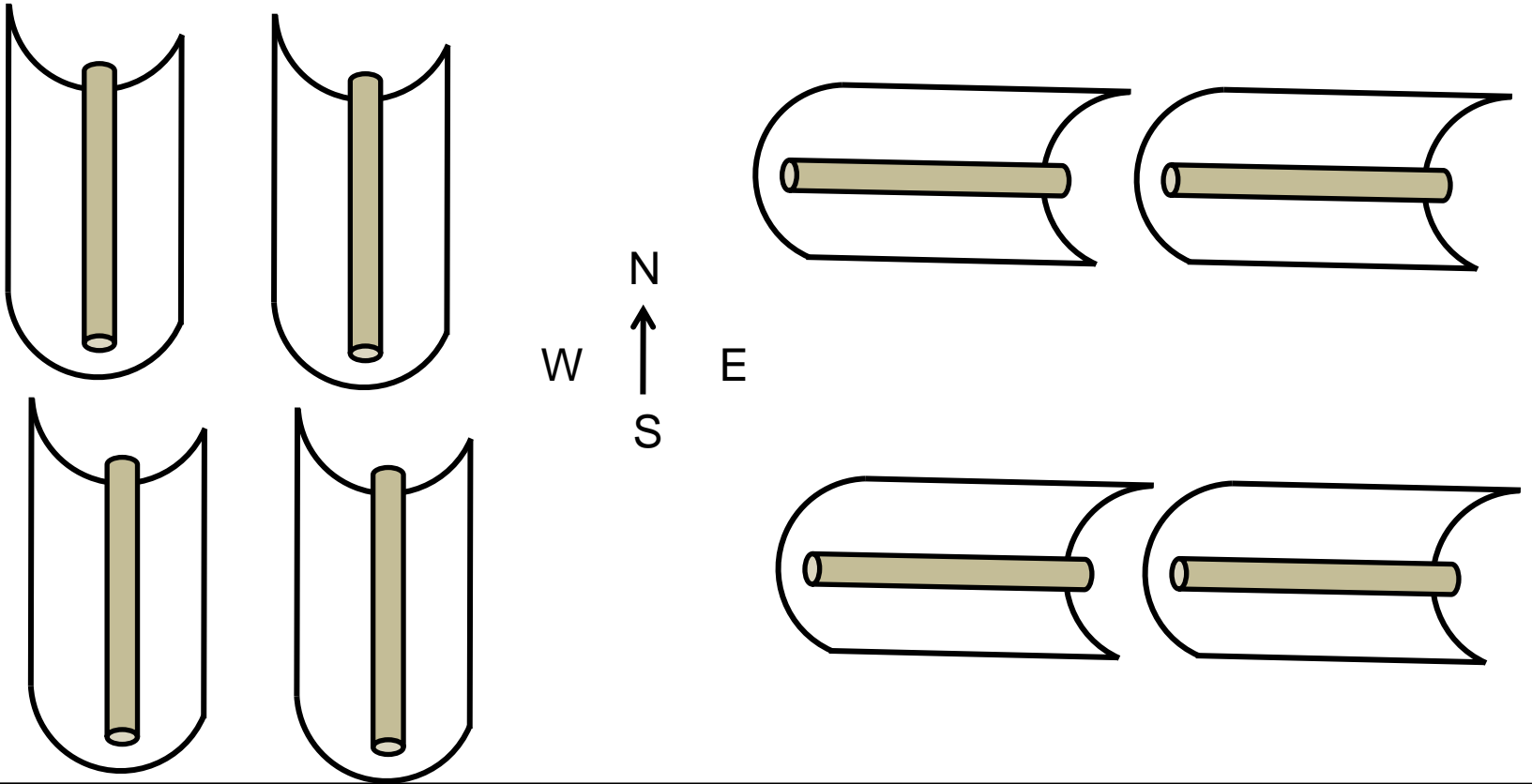
$$C = \frac{d}{\pi d_o} = \frac{7.5}{\pi(0.05)} = 47.75$$





# 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
- **East-West** layout: even distribution of energy production
- Select orientation for specific conditions (energy prices, load, etc)



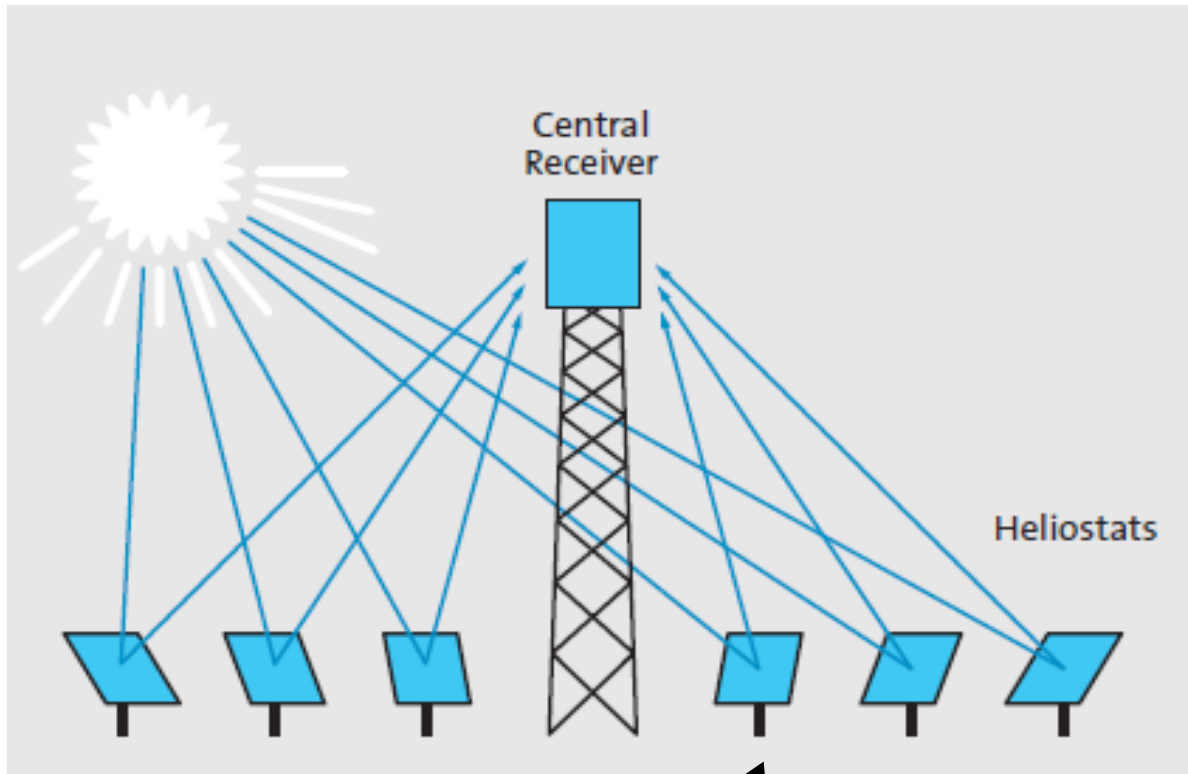
# PTC

- 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 °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





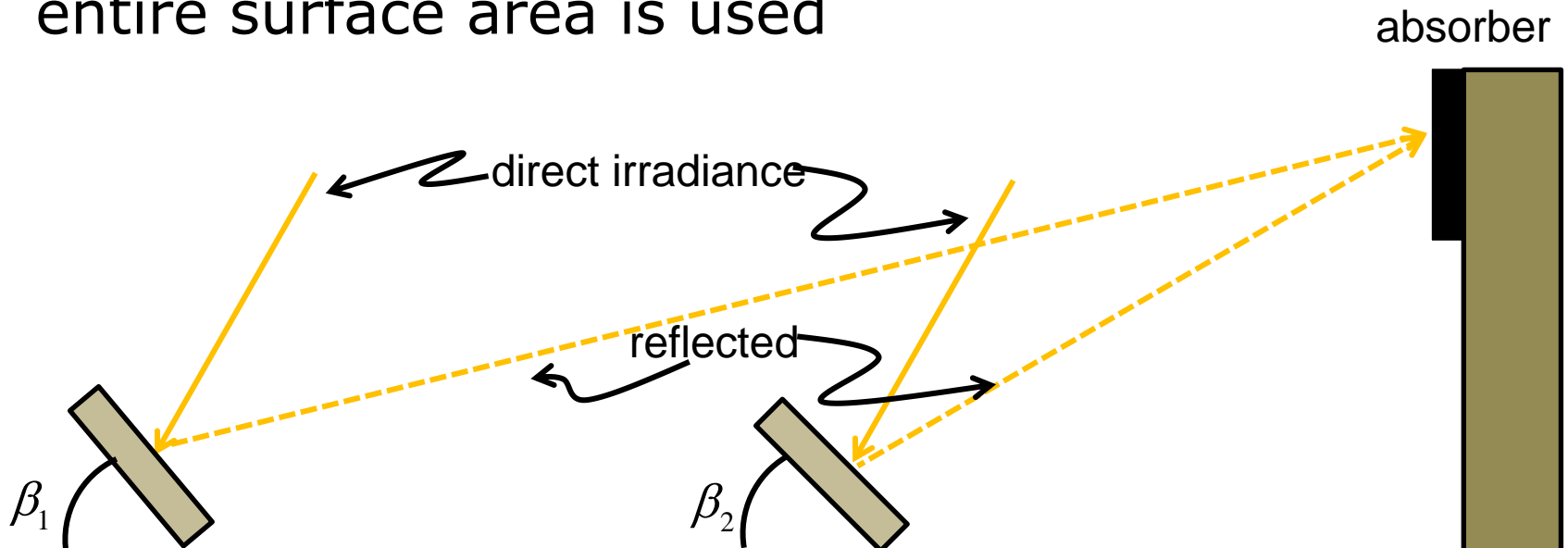
# Solar Tower Overview

- 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 °C):
  - hydrogen production or combustion turbine operation
  - efficient thermal storage (claimed to decrease overall cost of energy if included)
  - integration into fossil fuel plants

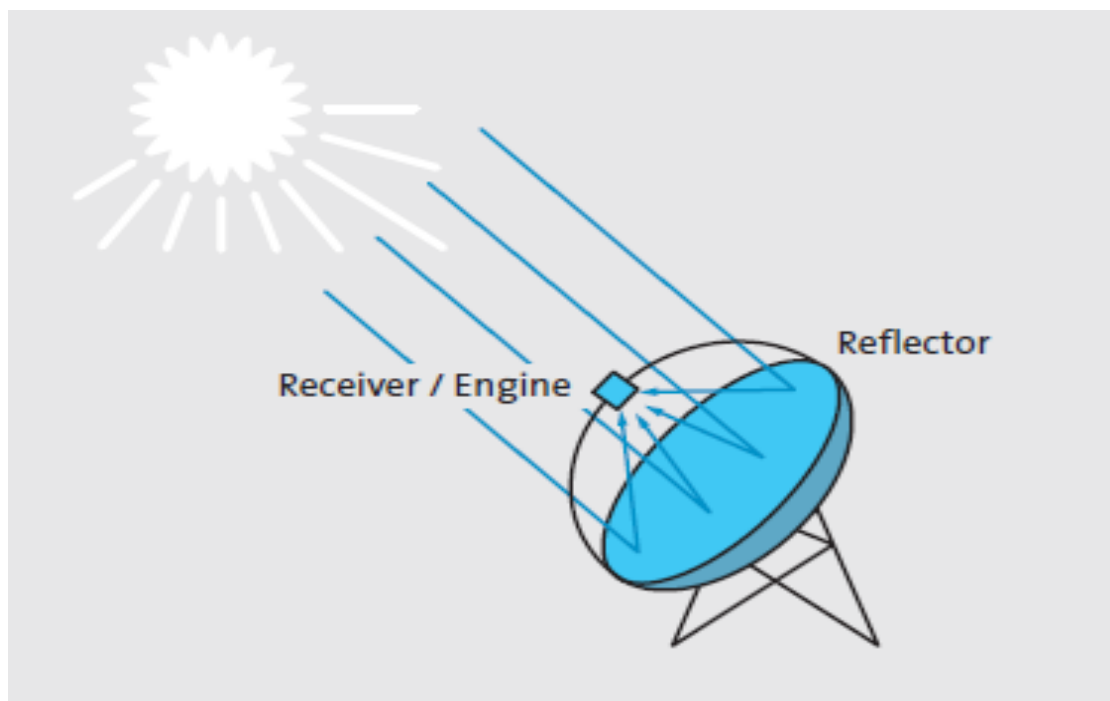


# Solar Tower Costs

- 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



# 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 °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



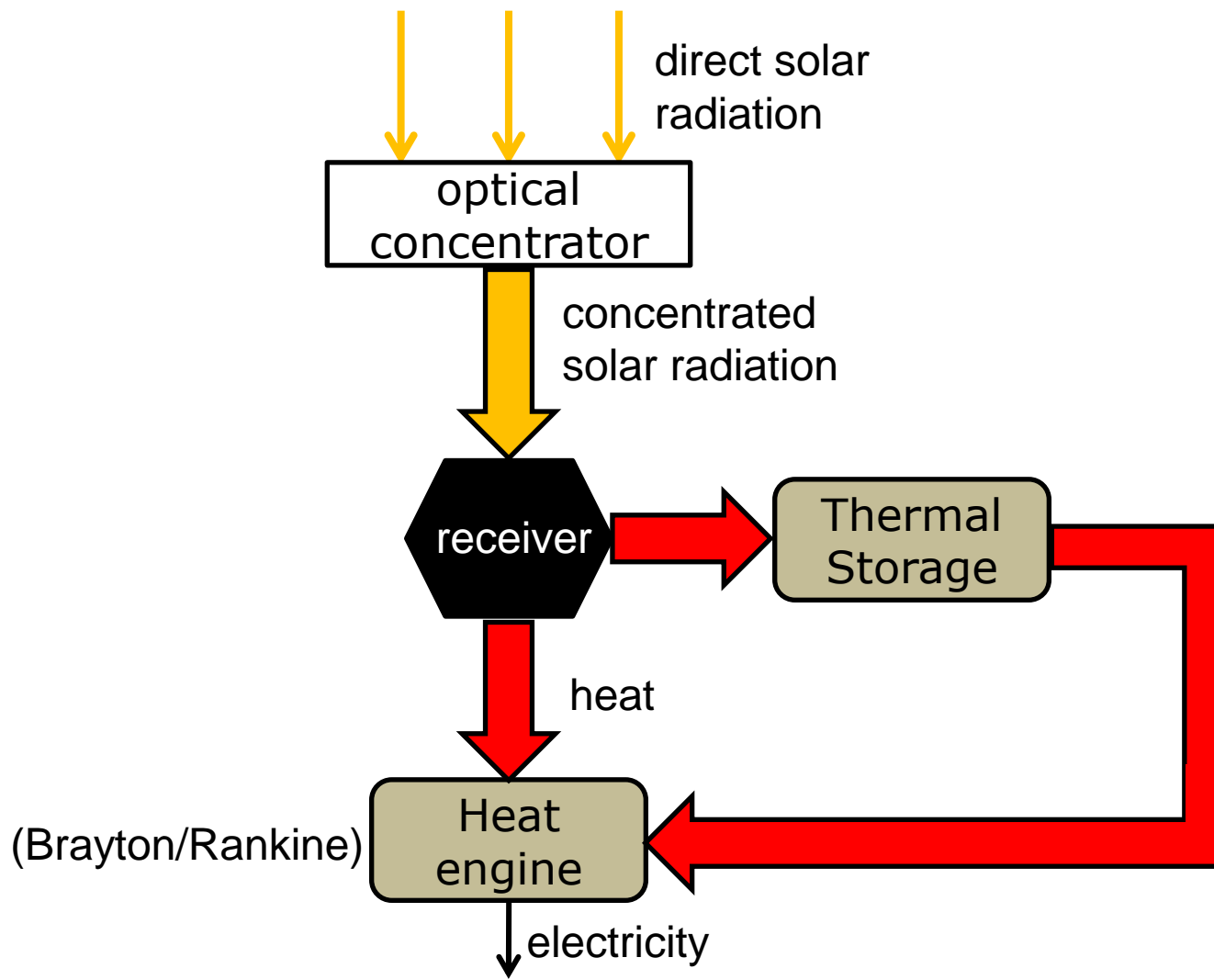
# Comparison

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

	<b>Parabolic Trough</b>	<b>Central Receiver</b>	<b>Parabolic Dish</b>
<b>Applications</b>	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)
<b>Advantages</b>	<ul style="list-style-type: none"> <li>• Commercially available operating temperature potential up to 500°C</li> <li>• Commercially proven annual net plant efficiency of 14%</li> <li>• Commercially proven investment and operating costs</li> <li>• Modularity</li> <li>• Best land-use factor of all solar technologies</li> <li>• Lowest materials demand</li> <li>• Hybrid concept proven</li> <li>• Storage capability</li> </ul>	<ul style="list-style-type: none"> <li>• Good mid-term prospects for high conversion efficiencies, operating temperature potential beyond 1,000°C</li> <li>• Storage at high temperatures</li> <li>• Hybrid operation possible</li> </ul>	<ul style="list-style-type: none"> <li>• Very high conversion efficiencies – peak solar to net electric conversion over 30%</li> <li>• Modularity</li> <li>• Hybrid operation possible</li> <li>• Operational experience of first demonstration projects</li> </ul>
<b>Disadvantages</b>	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 <ul style="list-style-type: none"> <li>• Projected cost goals of mass production still need to be achieved</li> </ul>



# Thermal Storage



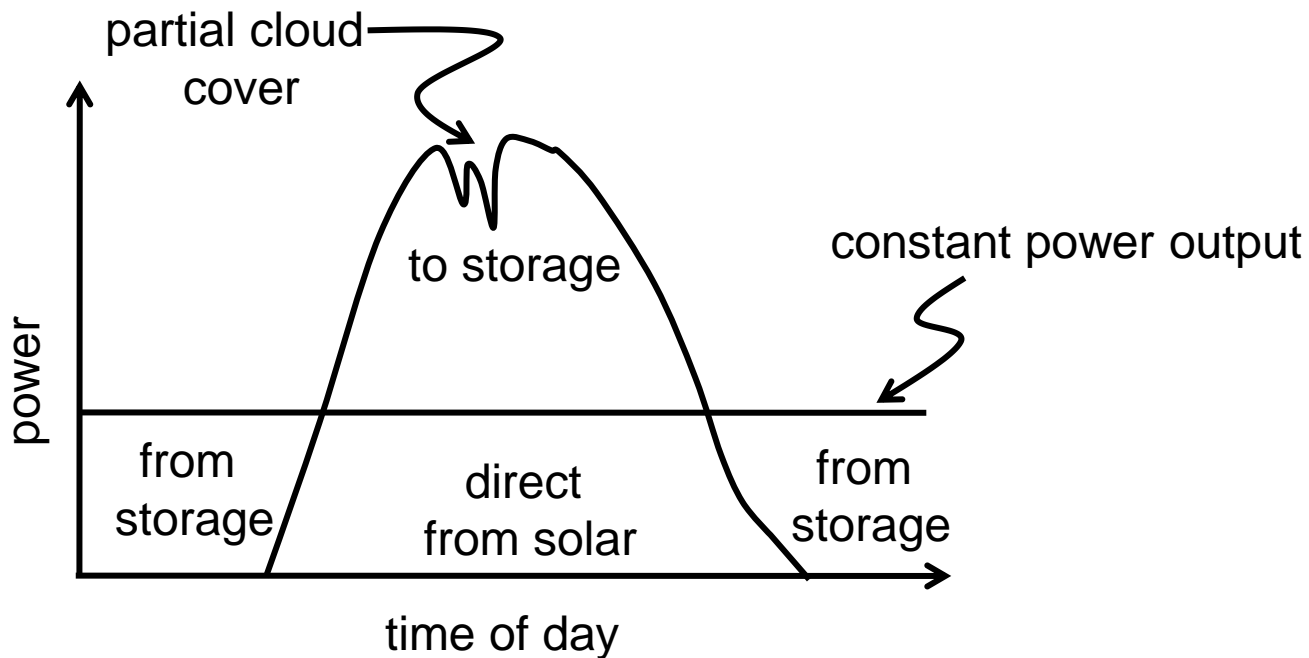


# Thermal Storage

- 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



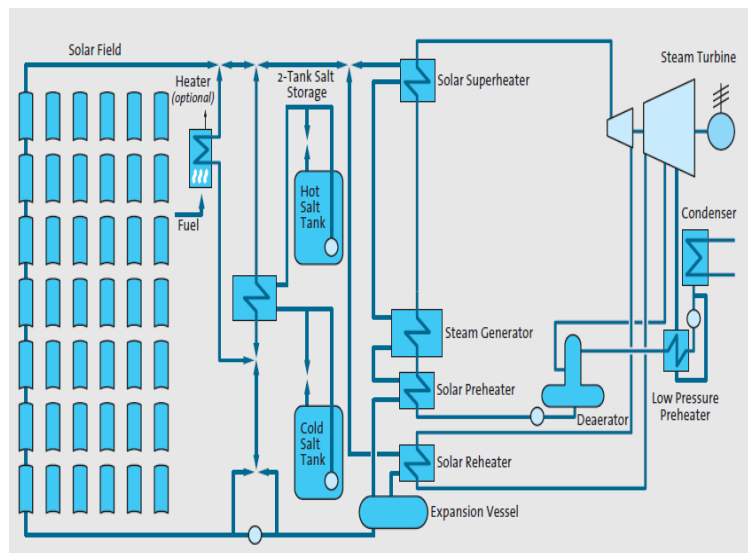
# Thermal Storage





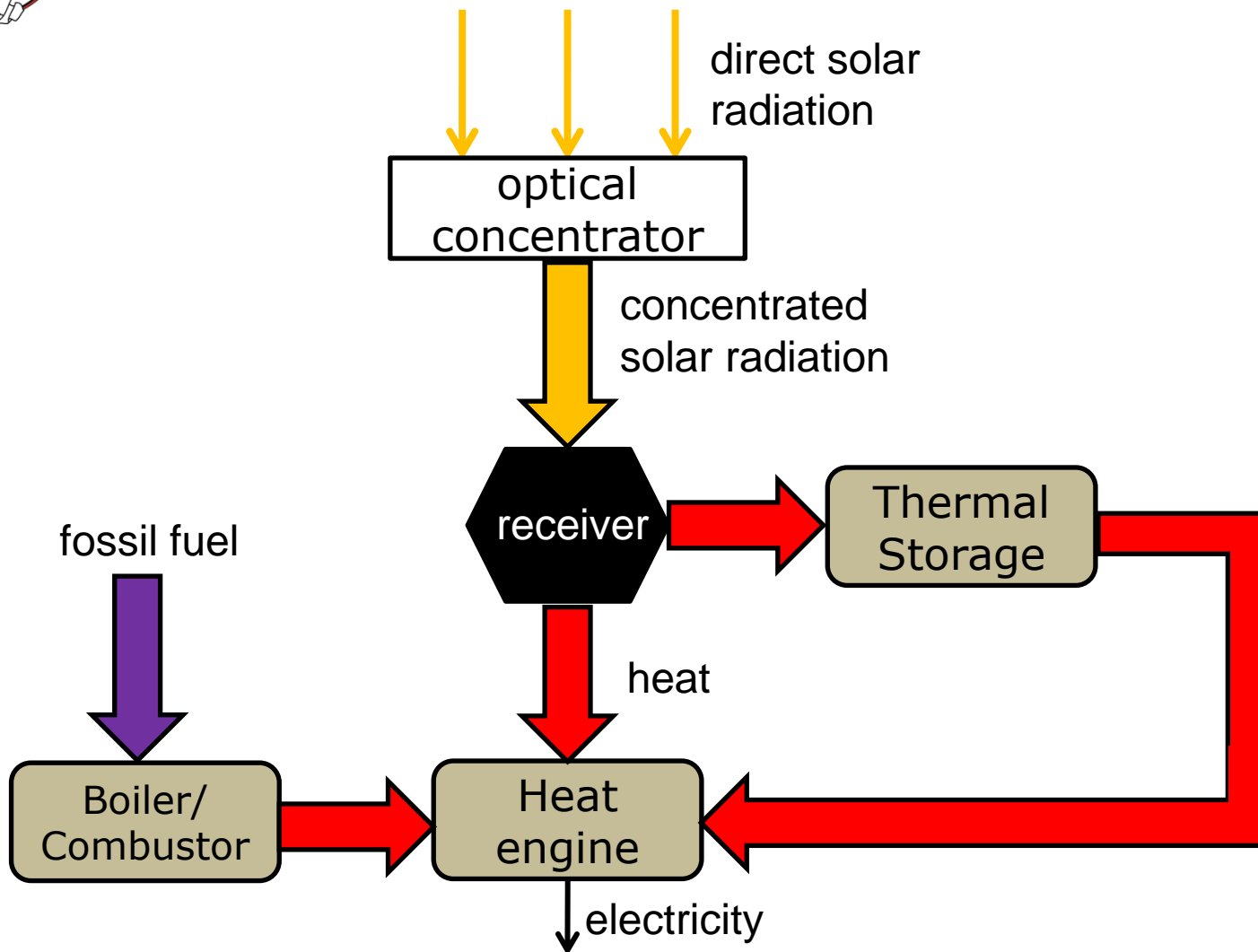
# Thermal Storage

- 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





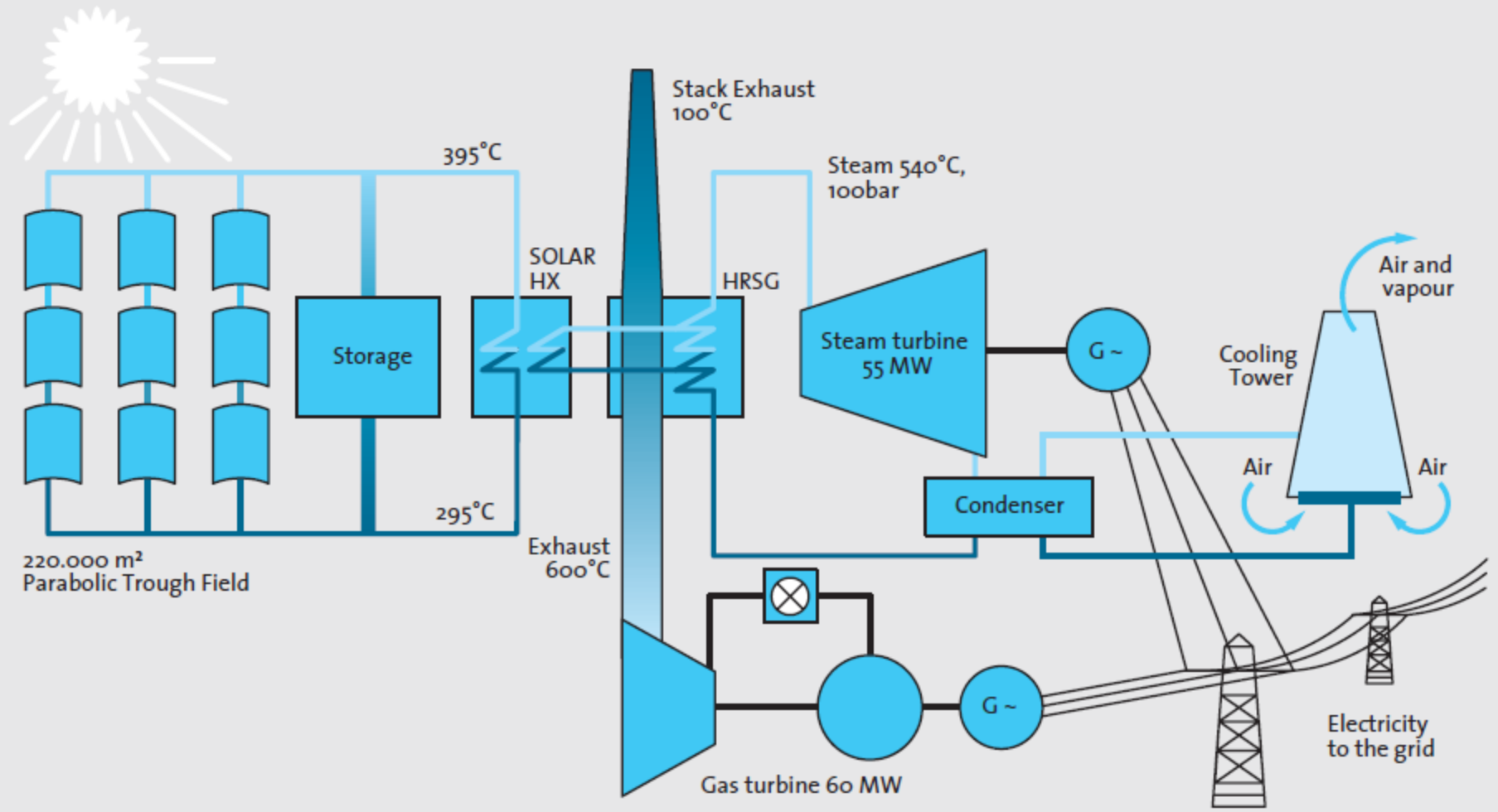
# Hybrid







# Integrated Solar Combined Cycle (ISCC)



Source: Centralized Solar Thermal Power Now!, Greenpeace