

19-Solar Thermal Basics

ECEGR 452

Renewable Energy Systems



Overview

- Introduction
- Concentrating Solar Power (CSP) Plant Principles
- CSP Technologies
- Concentration Ratio
- CSP Efficiency
- Stagnation



Introduction

- Solar radiation is converted to thermal energy when it is absorbed by an object
- Typical irradiance value is 1000 W/m^2

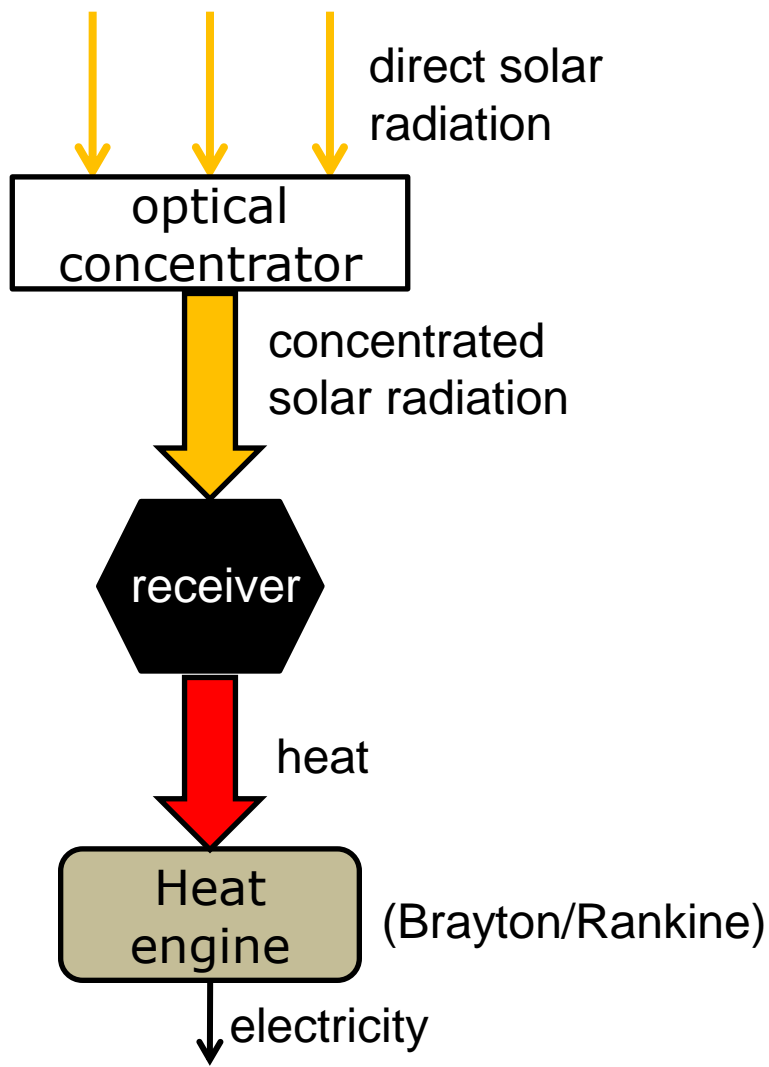


Introduction

- Three types of solar-thermal systems
 - Active solar heating: a separate collector is used
 - Passive solar heating: collection is integrated into the design of a building
 - **Solar thermal engines**: similar to active, but the thermal energy is used to drive an generator



Concentrating Solar Power (CSP)

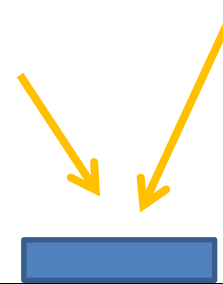




Solar Thermal Generation

- Concentrator: none
- Receiver: a small pool (1 m²) laying on the ground containing 100 liters of water
- Assume:
 - no reflection
 - no energy lost to surroundings

$$\text{GHI} = 1000 \text{ W/m}^2$$

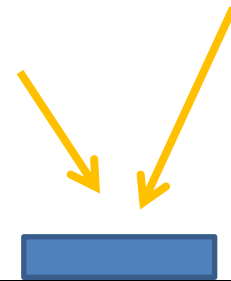




Solar Thermal Generation

- Ambient water temperature: 15° C
- After one hour: 3.6 MJ of solar radiation have been absorbed
- Assume:
 - no reflection
 - no energy lost to surroundings
- What is the temperature rise?

$$\text{GHI} = 1000 \text{ W/m}^2$$





Solar Thermal Generation

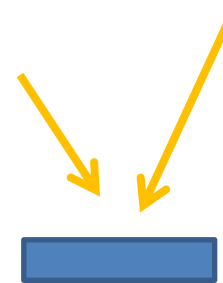
- How much has the temperature risen?

$$\Delta T = \frac{\Delta Q}{mc_h} = \frac{3.6MJ}{(100)(4186)} = 8.637 \text{ } ^\circ\text{C}$$

(specific heat of water is 4186 J/K)

- We now have water at 23.6 °C
- Can we use this heated water to create electricity?

GHI = 1000 W/m²

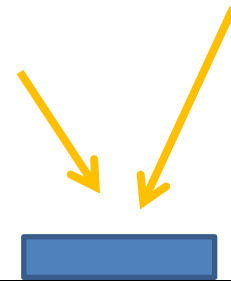




Solar Thermal Generation

- We cannot use it to generate electricity efficiently
- Temperature is too low

GHI = 1000 W/m²





Carnot Efficiency

- Upper limit on the efficiency of a process operating between two temperatures is dictated by the Carnot Efficiency

$$\eta_c = 1 - \frac{T_L}{T_H} = \frac{T_H - T_L}{T_H}$$

- Where
 - η_c : is the Carnot efficiency
 - T_L : is the cold reservoir temperature (K)
 - T_H : is the hot reservoir temperature (K)



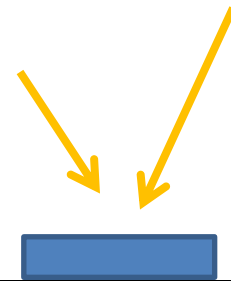
Solar Thermal Generation

- Assuming the cold reservoir is at ambient temperature, then the maximum efficiency is

$$\eta_C = \frac{T_H - T_C}{T_H} = \frac{296 - 288}{296} \approx 3\%$$

- Can you think of a more efficient design?

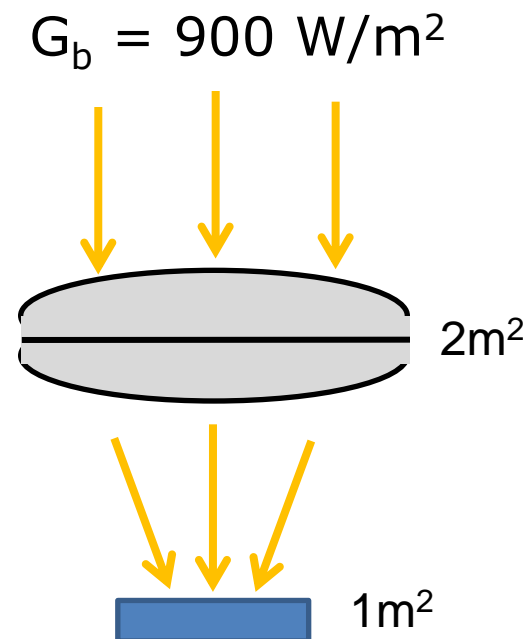
GHI = 1000 W/m²





Concentrating Solar Power (CSP)

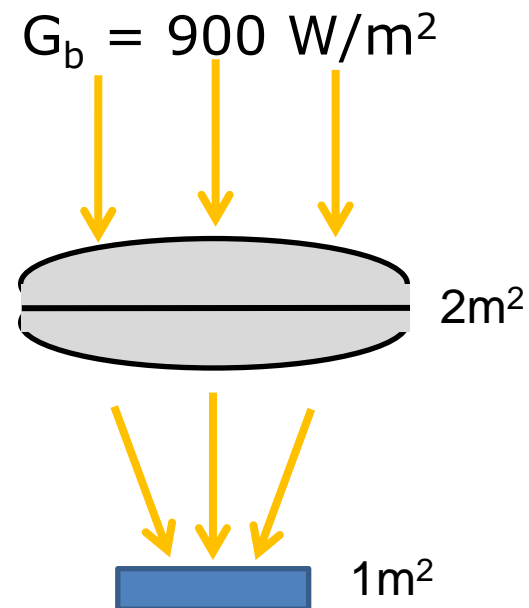
- Concentrator: lens
 - Assume the area of the lens shadow is 2m^2 (note this is NOT the surface area)
 - Diffuse irradiance (assumed to be 100 W/m^2 is not concentrated)
- Only direct radiation is focused
- Irradiance on the pool: 1800W/m^2





Concentrating Solar Power (CSP)

- What is the temperature of the pool after one hour under these conditions?
 - same assumptions as previous case
 - $T_{amb} = 15\text{ }^{\circ}\text{C}$





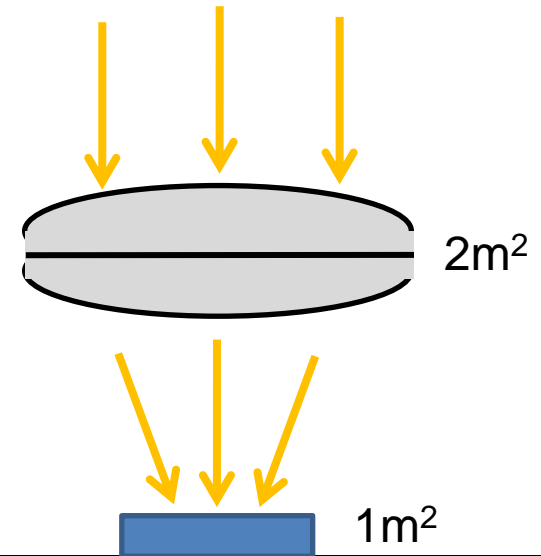
Concentrating Solar Power (CSP)

- What is the temperature of the pool after one hour under these conditions?

$$\Delta T = \frac{\Delta Q}{mc_h} = \frac{6.48MJ}{(100)(4186)} \approx 15.5 \text{ } ^\circ\text{C}$$

$$\Rightarrow T_H = 30.5 \text{ } ^\circ\text{C}$$

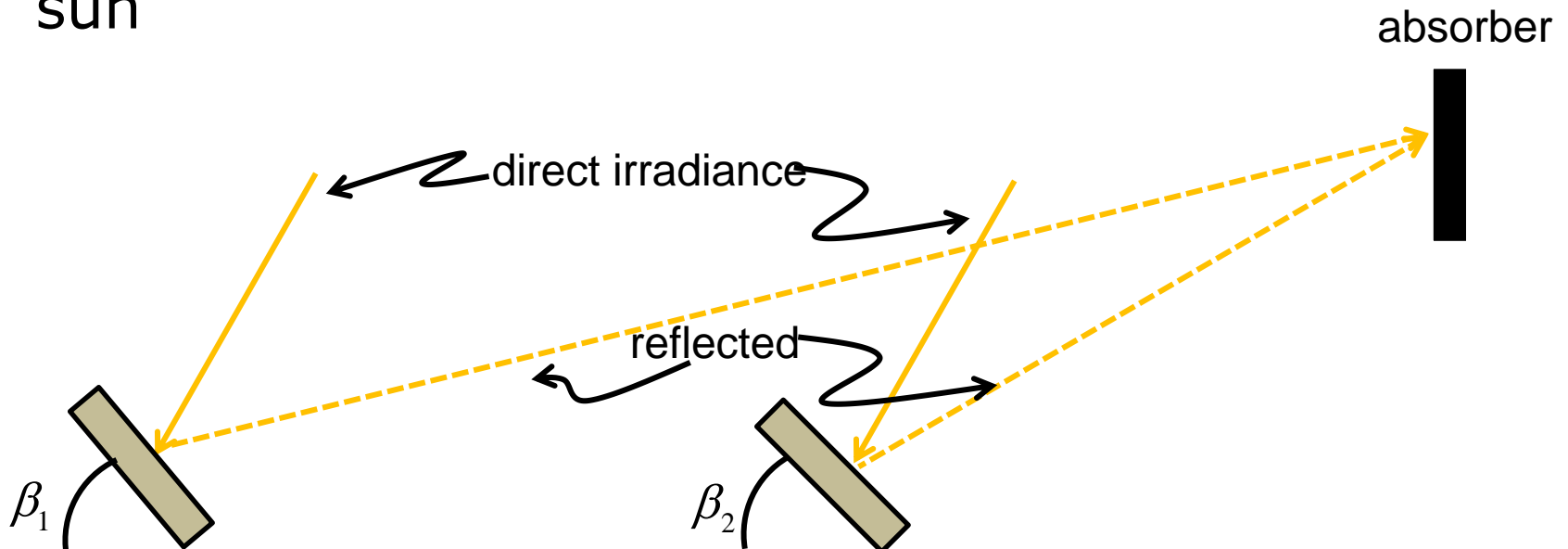
$$\eta_C = \frac{T_H - T_C}{T_H} \approx 5\% \text{ increased efficiency}$$





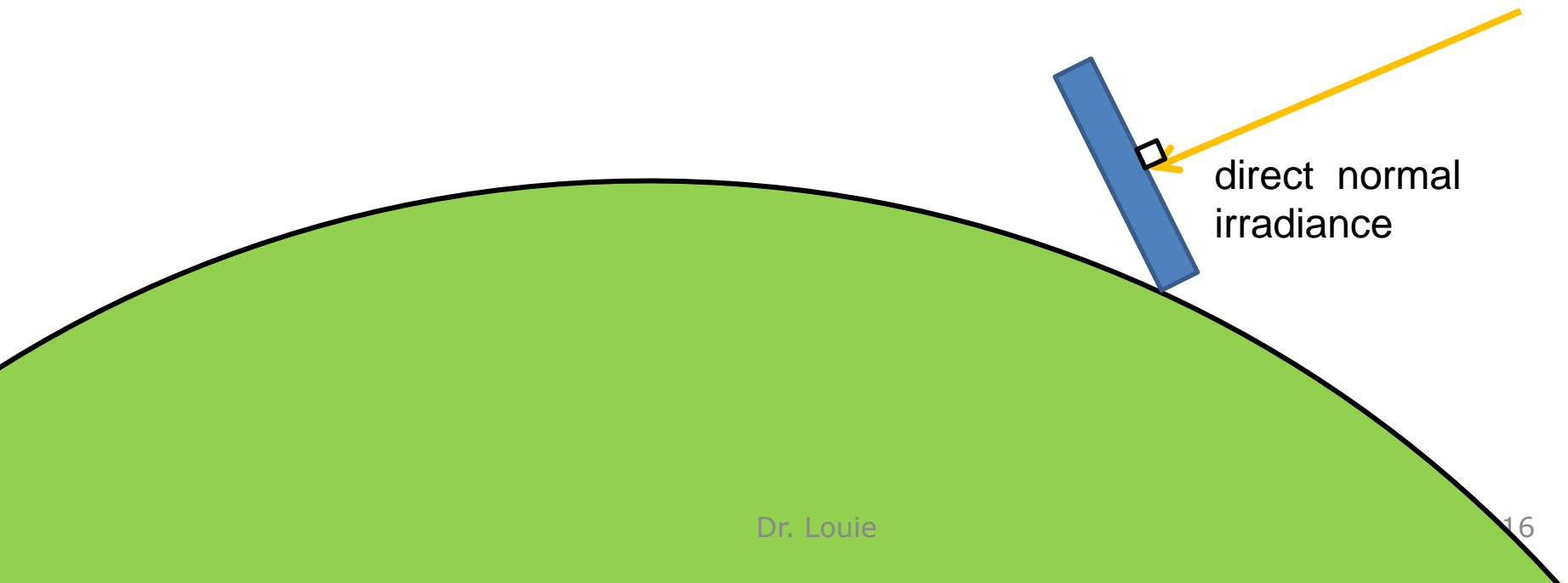
Concentrating Solar Power (CSP)

- Concentrator: mirrors
- Modeled from Snell's Law
- We will use G_{DNI} , assuming the mirrors track the sun



Direct Normal Irradiance

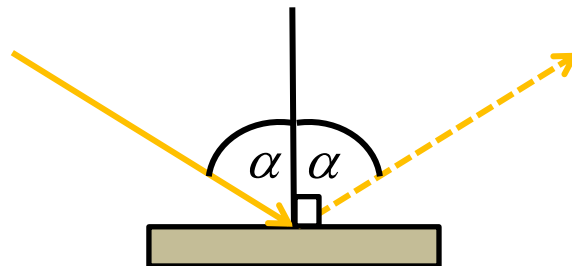
Direct Normal Irradiance: beam irradiance on a surface that is normal to the beam





Concentrating Solar Power (CSP)

Angle of reflected beam determined from Snell's Law





Concentrating Solar Power (CSP)

- **Fundamental operating premise:** Concentrated Solar Power (CSP) allows for “higher quality” energy to be converted due to the higher operating temperature of the heat engine
- What CSP configurations can you think of?

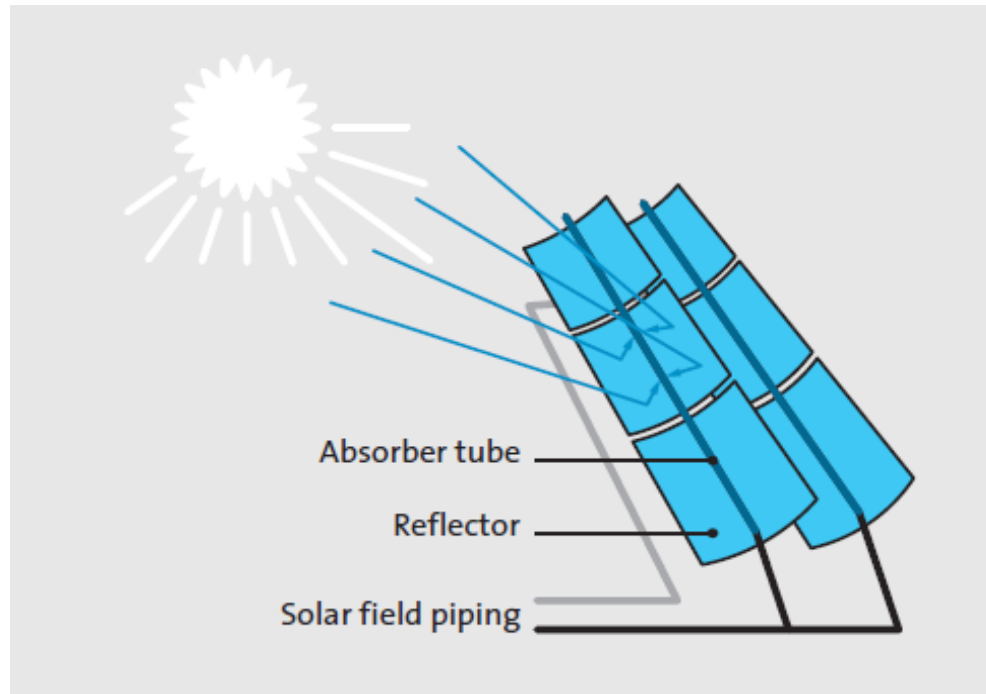


Types of CSP

- Four commercial or pilot project types:
 - Parabolic trough collector (PTC)
 - Centralized receiver systems (power towers)
 - Dish/engine systems
 - Linear Fresnel reflector

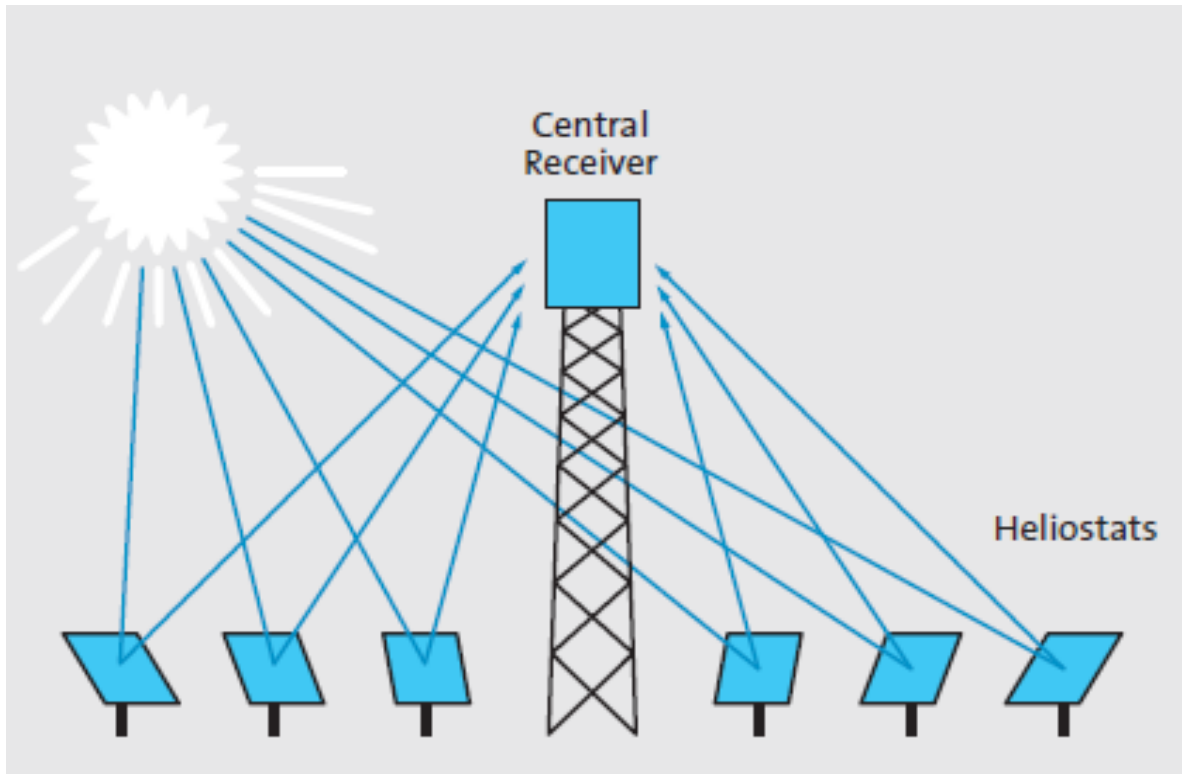


PTC



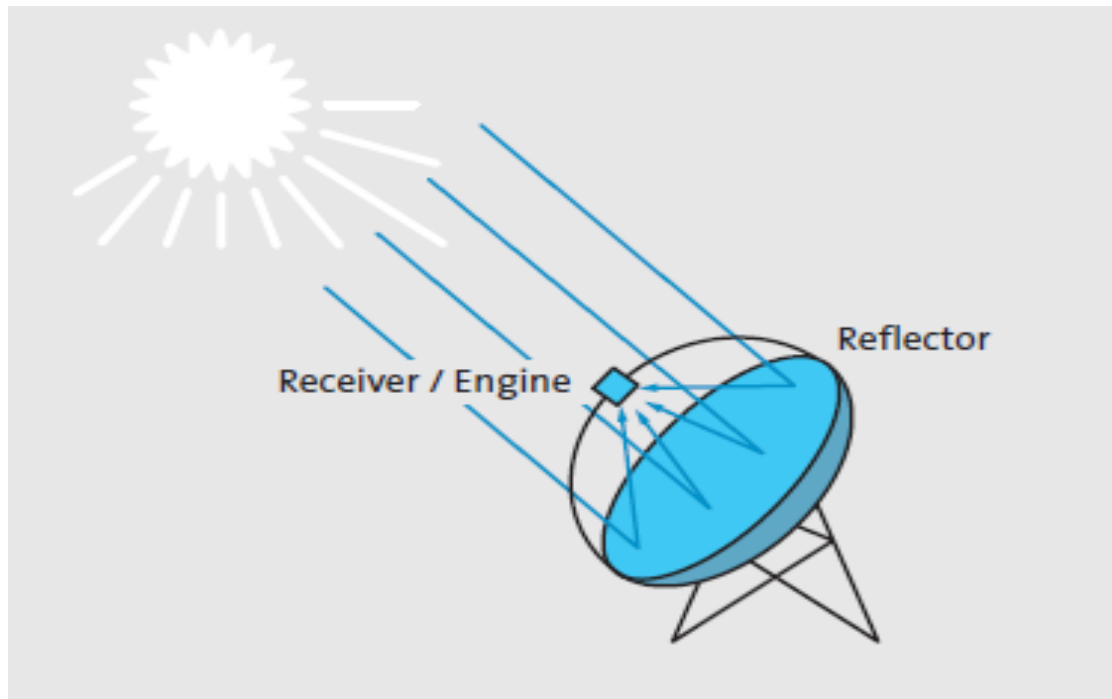


Power Tower





Dish





Concentration Ratio

- **Geometric concentration ratio**

$$C = \frac{A_C}{A_{rec}}$$

- A_C : area of collector
- A_{rec} : area of receiver
- “area” is interpreted as aperture area
- To heat a liquid to a high temperature, you need **large collector** area and/or a **small receiver** area



Example

- 25 mirrors with dimension 10m x 10m are used to concentrate beam irradiance (DNI) of 1000 W/m^2 on a receiver that is 5m x 5m. Find the:
 - geometric concentration ratio
 - irradiation received by the receiver



Example

- 25 mirrors with dimension 10m x 10m are used to concentrate beam irradiance (DNI) of 1000 W/m² on a receiver that is 5m x 5m. Find the:
 - geometric concentration ratio
 - irradiation received by the receiver

$$C = \frac{25 \times (10 \times 10)}{(5 \times 5)} = 100$$

$$\text{irradiance} = 100 \times 1000 = 100kW$$



Concentration Ratio

- What prevents us from using an arbitrarily small receiver to increase the concentration ratio?

$$C = \frac{A_c}{A_{rec}}$$

- Consider a surface with aperture of 100m^2 that focuses solar radiation on a receiver with area 0.001m^2
- What is the concentration ratio?



Concentration Ratio

- What prevents us from using an arbitrarily small receiver to increase the concentration ratio?

$$C = \frac{A_C}{A_{rec}}$$

- Consider a surface with aperture of 100m^2 that focuses solar radiation on a receiver with area 0.001m^2
- What is the concentration ratio?

$$C = \frac{100}{0.001} = 100,000$$



Concentration Ratio

- What is the irradiance on the receiver (if $G_{\text{DNI}} = 1,000 \text{ W/m}^2$)?



Concentration Ratio

- What is the irradiance on the receiver?

$$100,000 \times 1000 \text{ W/m}^2 = 100 \text{ MW/m}^2$$

- This greater than the irradiance at the surface of the Sun (about 63 MW/m^2)!
- Second law of thermodynamics prevents this



Concentration Ratio

- The actual limit is

$$C < \left(\frac{R}{r} \right)^2 \approx 45,000$$

- R : mean distance from the Earth to the Sun
- r : radius of the Sun



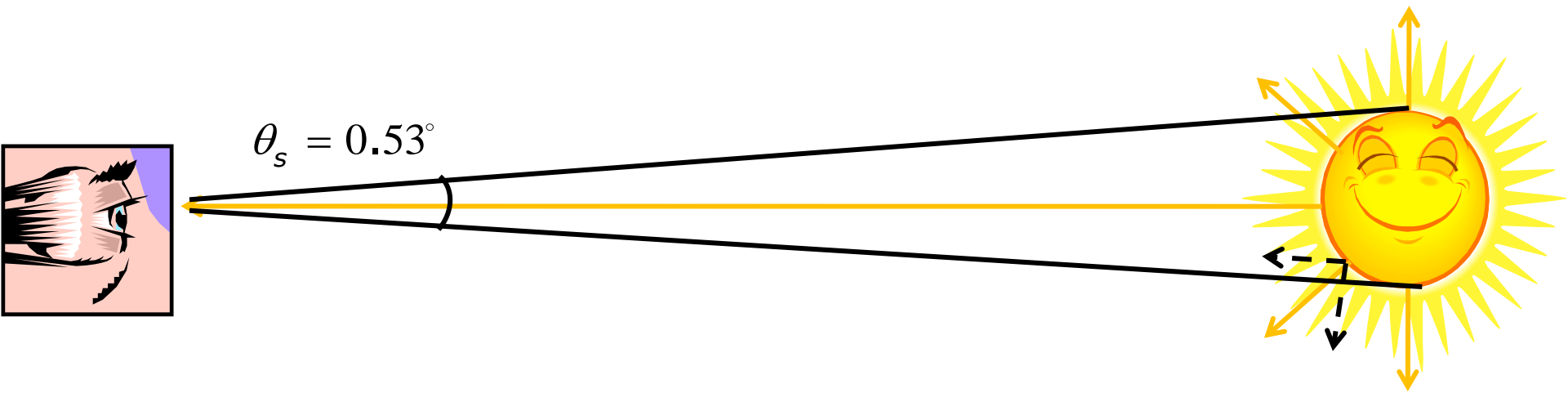
Concentration Ratio

- Actual concentration ratios are much smaller (< 5000), depending on the collector arrangement
- It is useful to consider the size of the reflected image of the Sun
- Sun does not appear as a point, it appears as a disc



Concentration Ratio

subtended solid angle of 0.53°





Side Note

- Angle subtended by the moon is also about 0.53°
- This is why a "Ring of Fire" eclipse can occur



Source: National Geographic

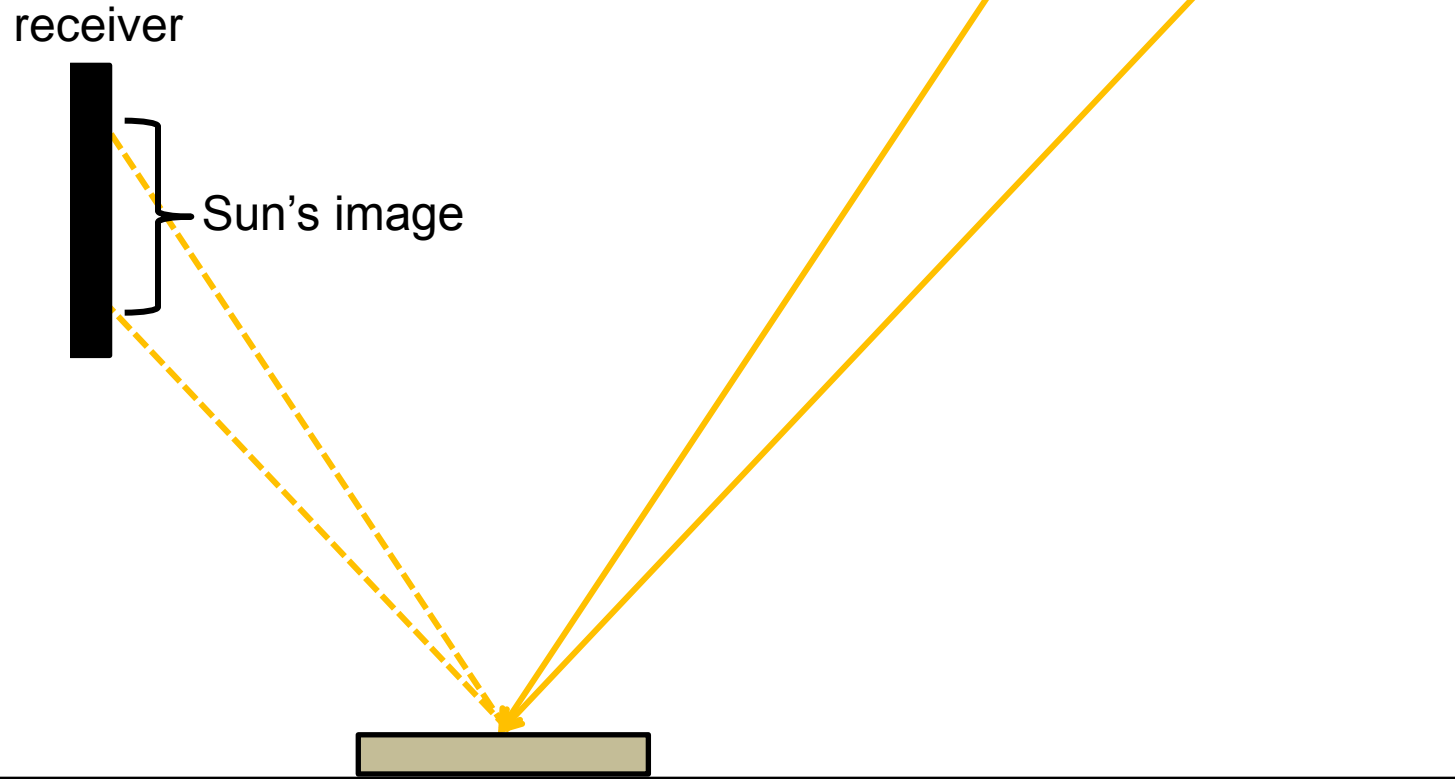
Reflected Image

reflected image of the Sun will always have
a target-to-mirror solid angle equal to 0.53°
Sun's rays cannot be focused to a single point!

receiver



Sun's image





CSP Process

- CSPs concentrate irradiation, G_{DNI} , from the collector to receiver

$$G_C = \alpha C G_{DNI}$$

- G_C = irradiance **from** the collector (W/m^2)
- α is the absorptivity (unitless, ≤ 1)



CSP Efficiency

- Temperature of the receiver, T_{rec} , increases
 - thermal energy, Q , is transferred to a working fluid in the receiver
 - as T_{rec} increases above the ambient temperature, T_{amb} , it begins to transfer heat via radiation (convection and conduction heat transfer are ignored)
 - **Thermal energy is lost**
 - How is the radiated power determined?



CSP Efficiency

- Recall the Stefan-Boltzmann Law:

$$G = \sigma T^4 \text{ W/m}^2$$

$$\sigma = 5.67 \times 10^{-8} \text{ J/(sm}^2\text{K}^4)$$

- If the object is not a black body, then:

$$G = \sigma \varepsilon T^4 \text{ W/m}^2$$

- ε is the emissivity of the object (unitless)

- Surrounding environment is also radiating energy toward the receiver

- net irradiance:

$$G_{rec} = \sigma \varepsilon (T_{rec}^4 - T_{amb}^4)$$



CSP Efficiency

- Net flow of heat:

$$\dot{Q} = A_C (G_C - G_{rec}) W$$

$$\dot{Q} = A_C (\alpha_C G_{DNI} - \sigma \varepsilon (T_{rec}^4 - T_{amb}^4)) W$$

- Receiver efficiency:

$$\eta_{rec} = \frac{\dot{Q}}{A_C G_{DNI}}$$



CSP Efficiency

- Efficiency:

$$\eta_{rec} = \frac{\dot{Q}}{AC_C G_{DNI}} = \left(\alpha - \sigma \varepsilon \frac{(T_{rec}^4 - T_{amb}^4)}{CG_{DNI}} \right)$$

- Assume $T_{rec} > T_{amb}$
- What happens to the efficiency of the receiver if:
 - Concentration ratio (C) increases?
 - T_{rec} increases?
- What is the maximum efficiency?



CSP Efficiency

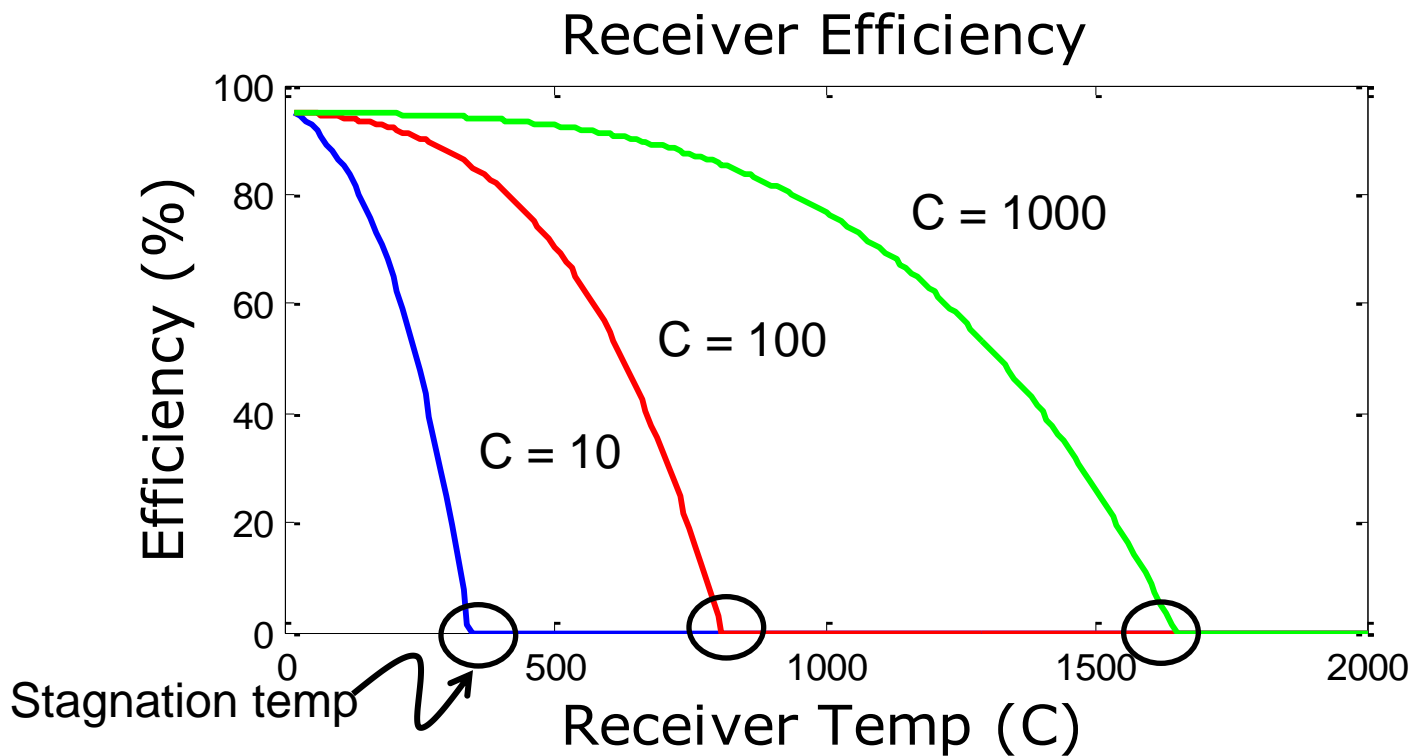
- Efficiency:

$$\eta_{rec} = \frac{\dot{Q}}{ACG_{DNI}} = \left(\alpha - \sigma \varepsilon \frac{(T_{rec}^4 - T_{amb}^4)}{CG_{DNI}} \right)$$

- assume $T_{rec} > T_{amb}$
- What happens to the efficiency of the receiver if:
 - Concentration ratio increases?
 - efficiency increases
 - T_{rec} increases?
 - efficiency decreases
- What is the maximum efficiency?
 - α



CSP Efficiency



With: $T_{amb} = 20$ C; $\varepsilon = \alpha = .95$; $G_{DNI} = 770$ W/m²



CSP Efficiency

- CSPs use heat engines
- System efficiency:

$$\eta_{CSP} = \eta_C \eta_{rec}$$

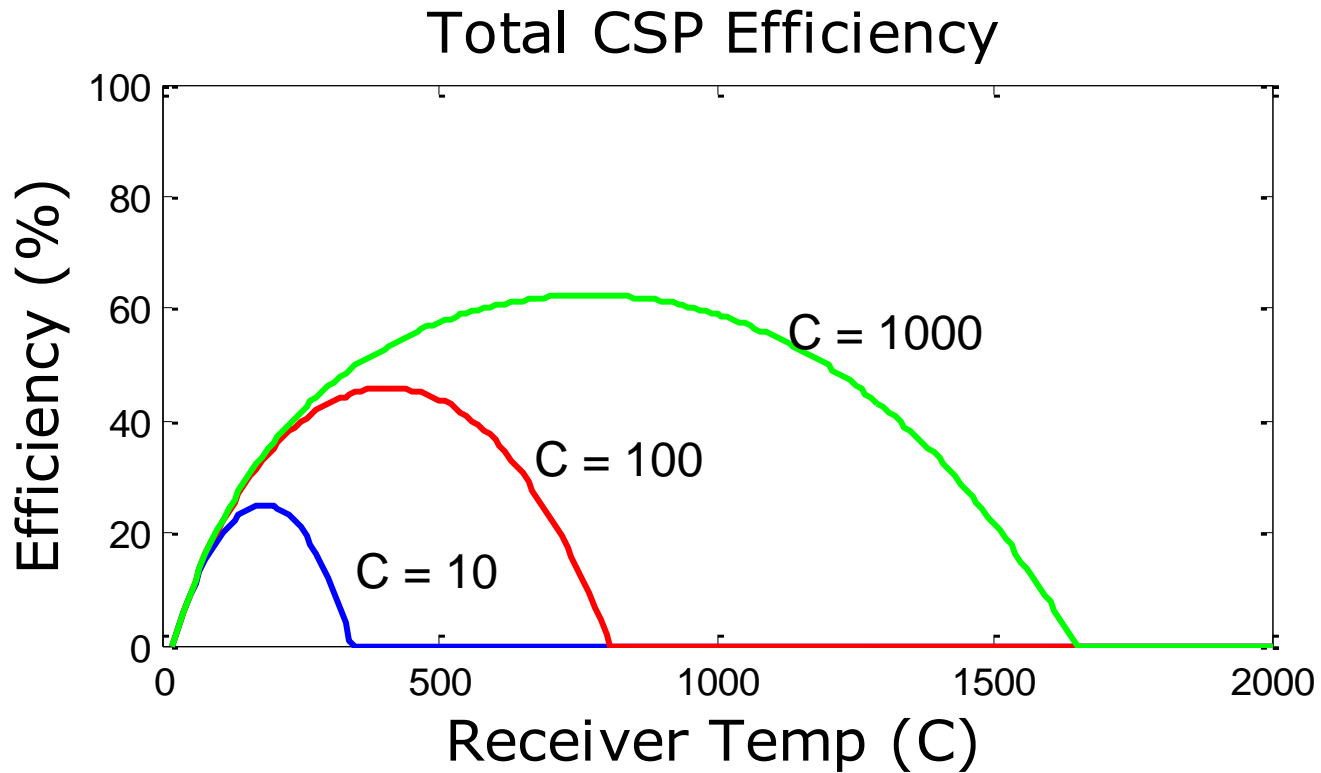
- Carnot efficiency increases with temperature

$$\eta_C = \frac{T_{rec} - T_{amb}}{T_{rec}}$$

- Which efficiency dominates?



CSP Efficiency





CSP Efficiency Example

- A typical concentration ratio for a PTC CSP is 70. Find the receiver efficiency, Carnot efficiency and total efficiency if:

$$T_{rec} = 400 \text{ }^{\circ}\text{C}, T_{amb} = 20 \text{ }^{\circ}\text{C}; \varepsilon = \alpha = 1;$$

$$G_{DNI} = 800 \text{ W/m}^2$$



CSP Efficiency Example

- A typical concentration ratio for a PTC CSP is 70. Find the receiver efficiency, Carnot efficiency and total efficiency if:

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- Receiver efficiency:

$$\eta_{rec} = \left(\alpha - \sigma \varepsilon \frac{(T_{rec}^4 - T_{amb}^4)}{CG_{DNI}} \right) = \left(1 - \sigma \frac{(673^4 - 293^4)}{70 \times 800} \right) \approx 76\%$$



CSP Efficiency Example

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- Carnot efficiency:

$$\eta_C = \frac{T_{rec} - T_{amb}}{T_{rec}} = \left(\frac{673 - 293}{673} \right) \approx 56\%$$



CSP Efficiency Example

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- Total efficiency:

$$\eta_{CSP} = \eta_C \eta_{rec}$$



CSP Efficiency Example

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$$G_{DNI} = 800 \text{ W/m}^2$$

- Total efficiency:

$$\eta_{CSP} = \eta_C \eta_{rec} \approx 42\%$$



CSP Efficiency

