16-Solar Thermal Basics

ECEGR 4530

Renewable Energy Systems

Overview

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

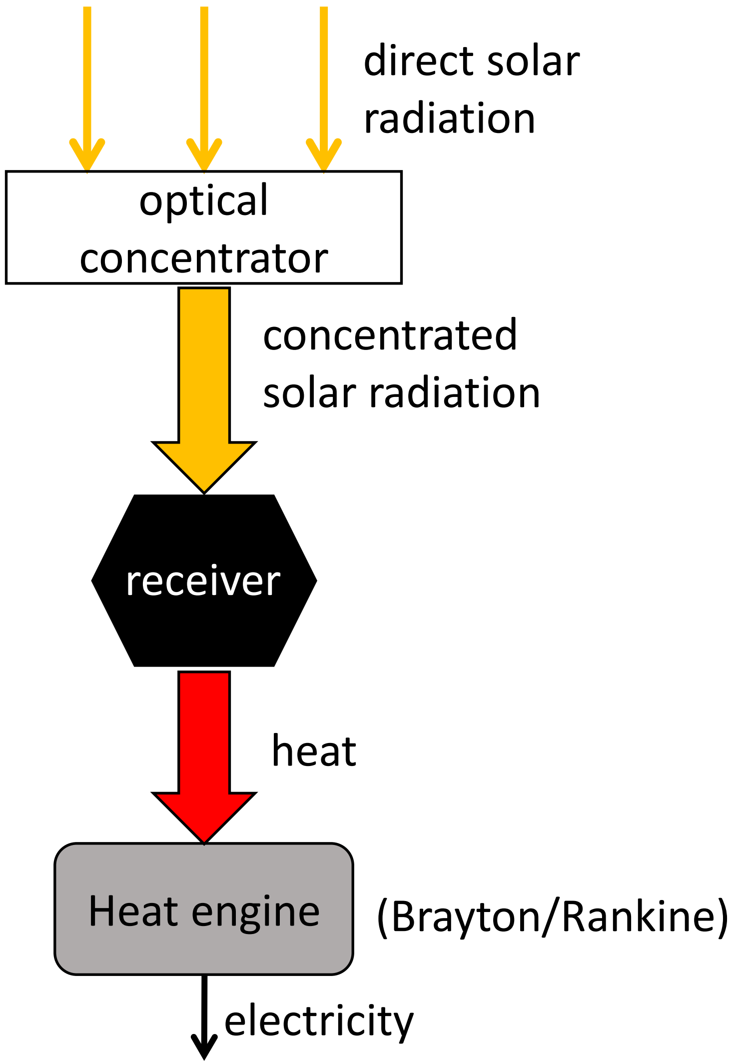
Introduction

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

Introduction

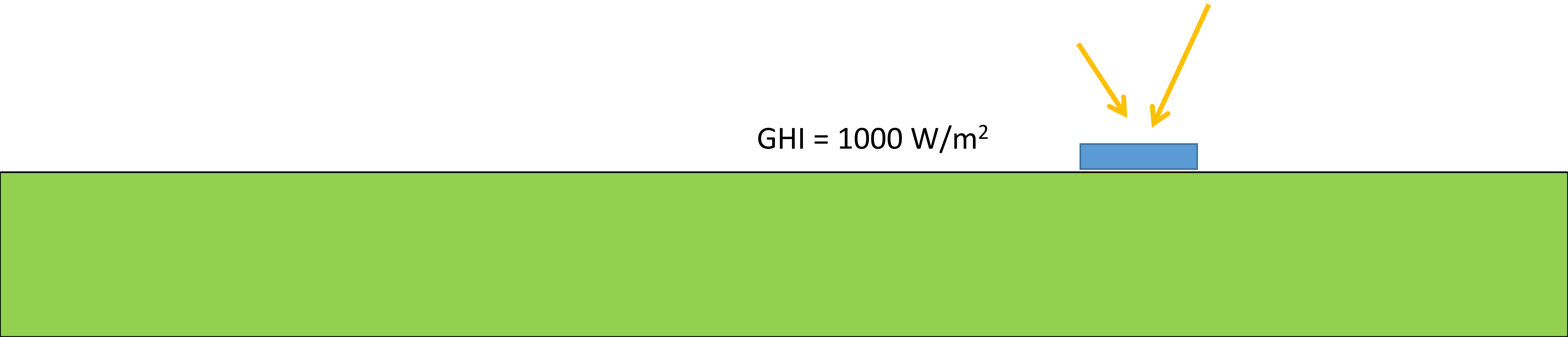
- Three types of solar-thermal systems
  - Active solar heating: a separate collector is used
  - Passive solar heating: collection is integrated into the design of a building
  - Solar thermal engines: similar to active, but the thermal energy is used to drive an generator

Concentrating Solar Power (CSP)



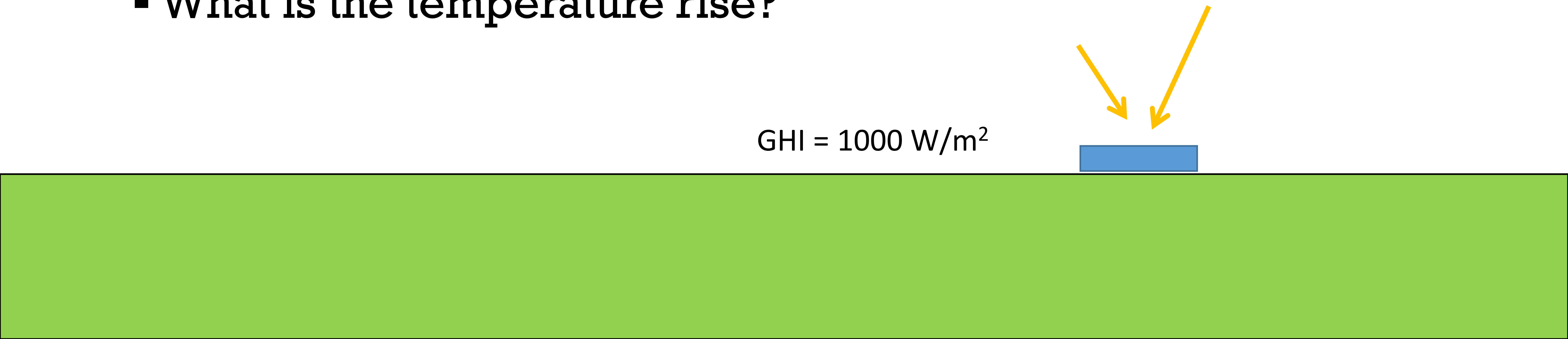
Solar Thermal Generation

- Concentrator: none
- Receiver: a small pool (1 m^2) laying on the ground containing 100 liters of water
- Assume:
  - no reflection
  - no energy lost to surroundings



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?



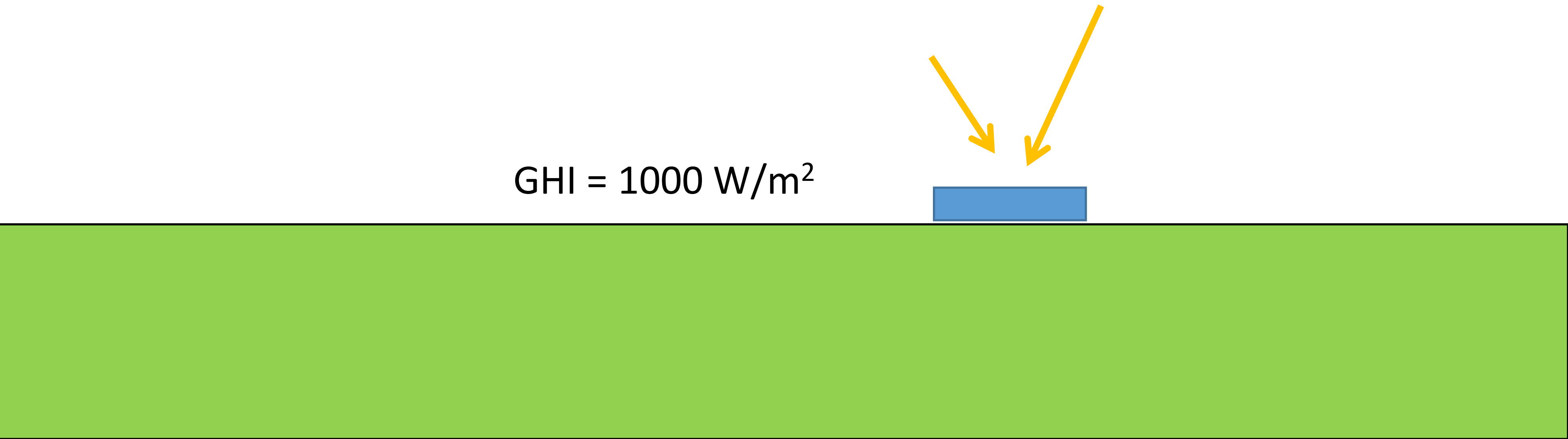
Solar Thermal Generation

- How much has the temperature risen?

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

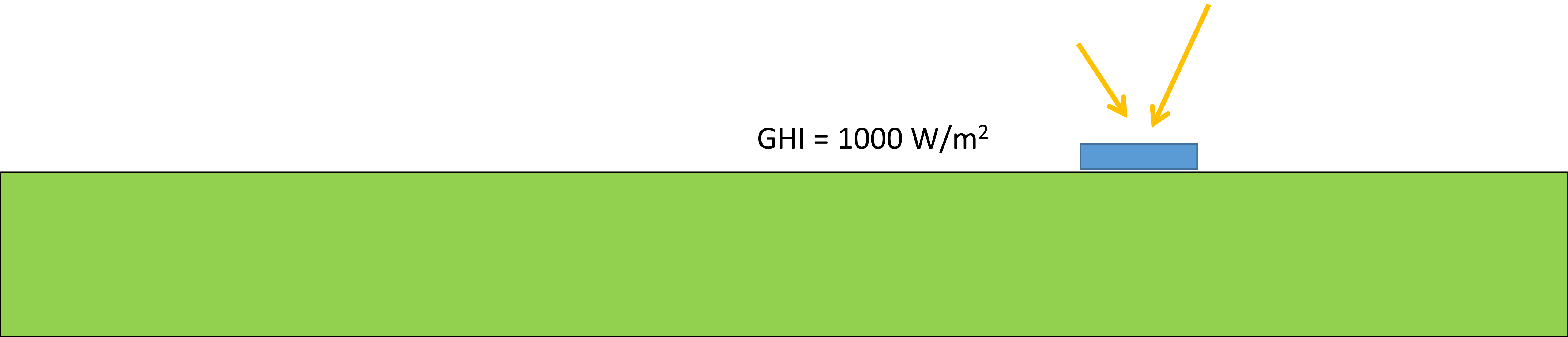
(specific heat of water is 4186 J/K)

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



Solar Thermal Generation

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



Carnot Efficiency

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

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

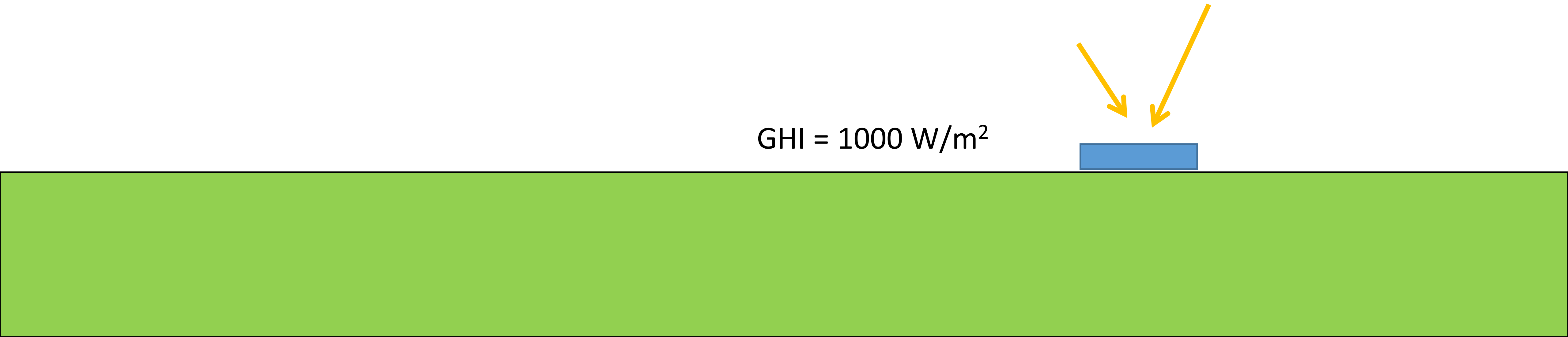
- Where
  - η_C: is the Carnot efficiency
  - T_L: is the cold reservoir temperature (K)
  - T_H: is the hot reservoir temperature (K)

Solar Thermal Generation

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

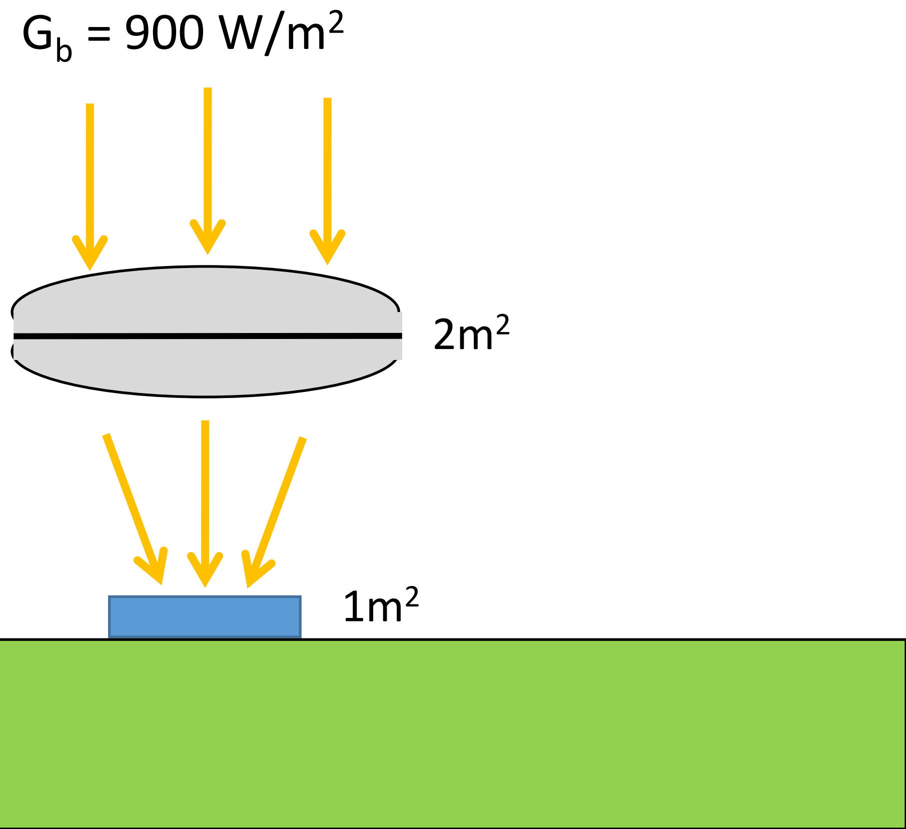
$$\eta_C = \frac{T_H - T_C}{T_H} = \frac{296 - 288}{296} \approx 3\%$$

- Can you think of a more efficient design?



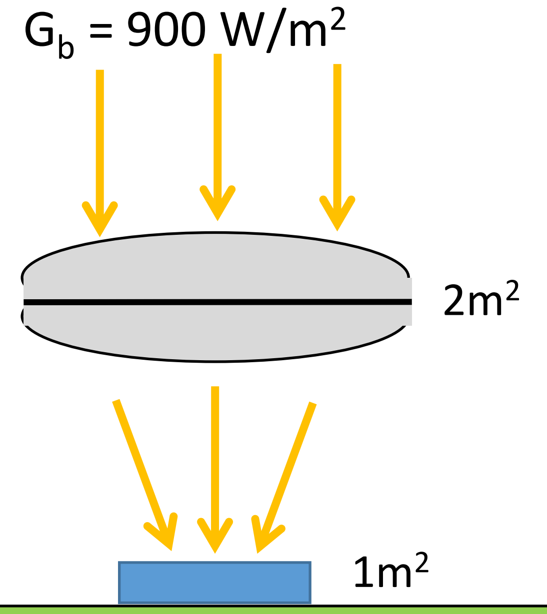
Concentrating Solar Power (CSP)

- 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 °C



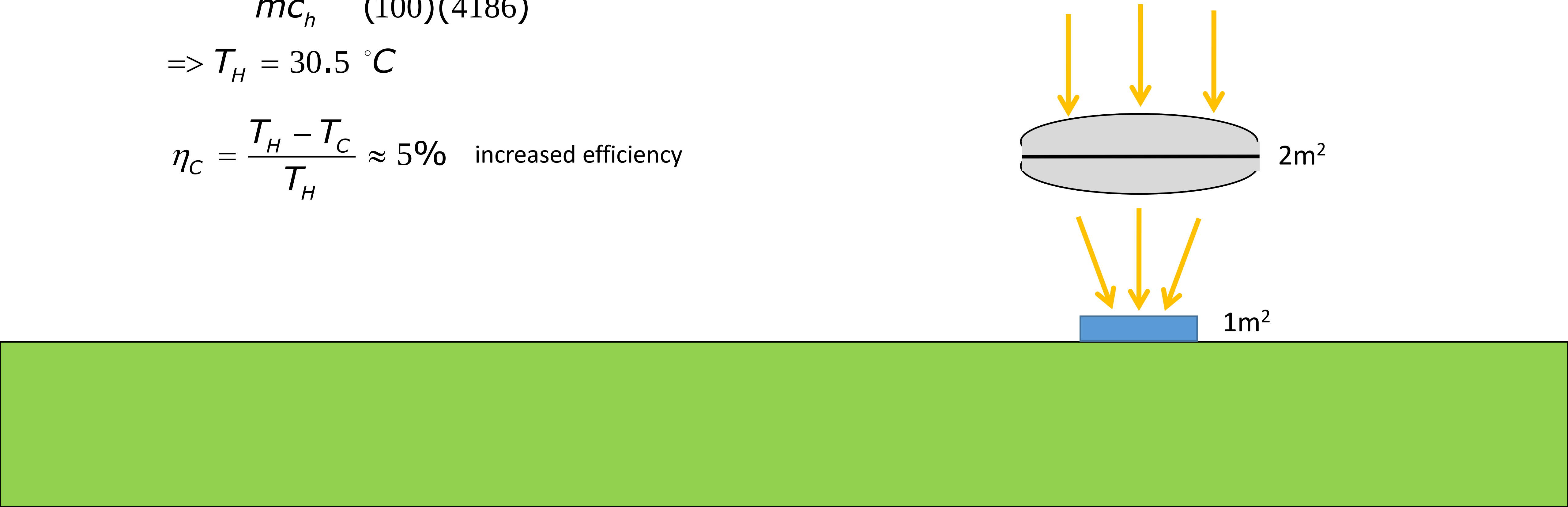
Concentrating Solar Power (CSP)

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

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

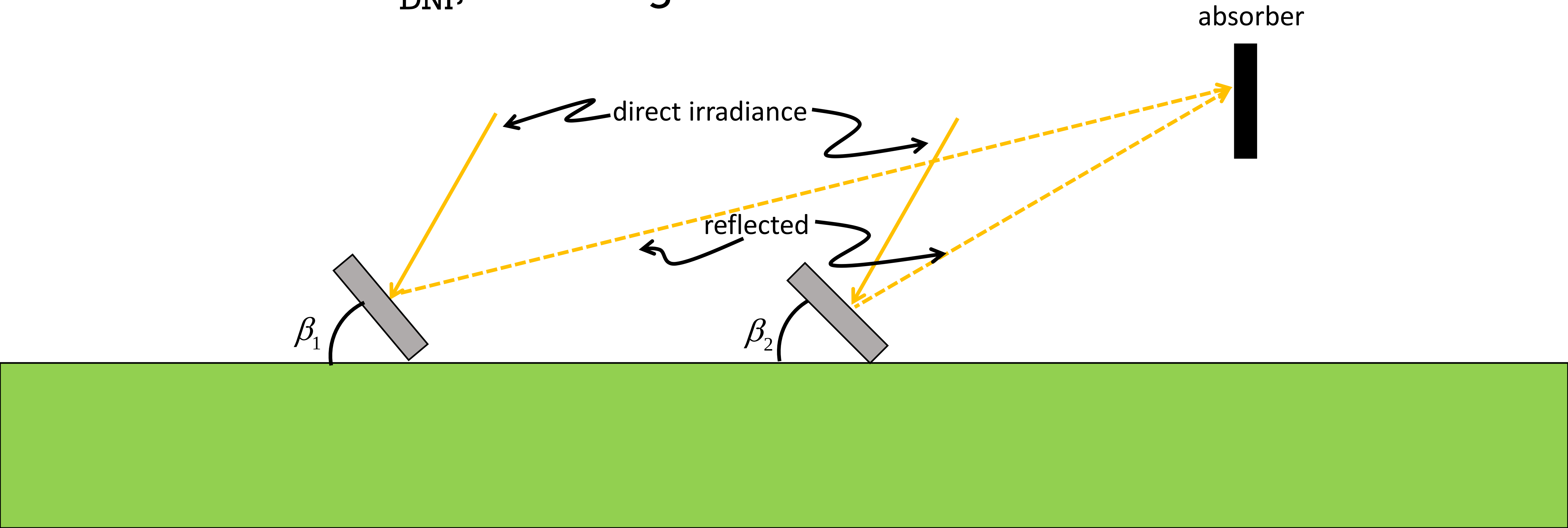
$$=> T_H = 30.5\ ^{\circ}C$$

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



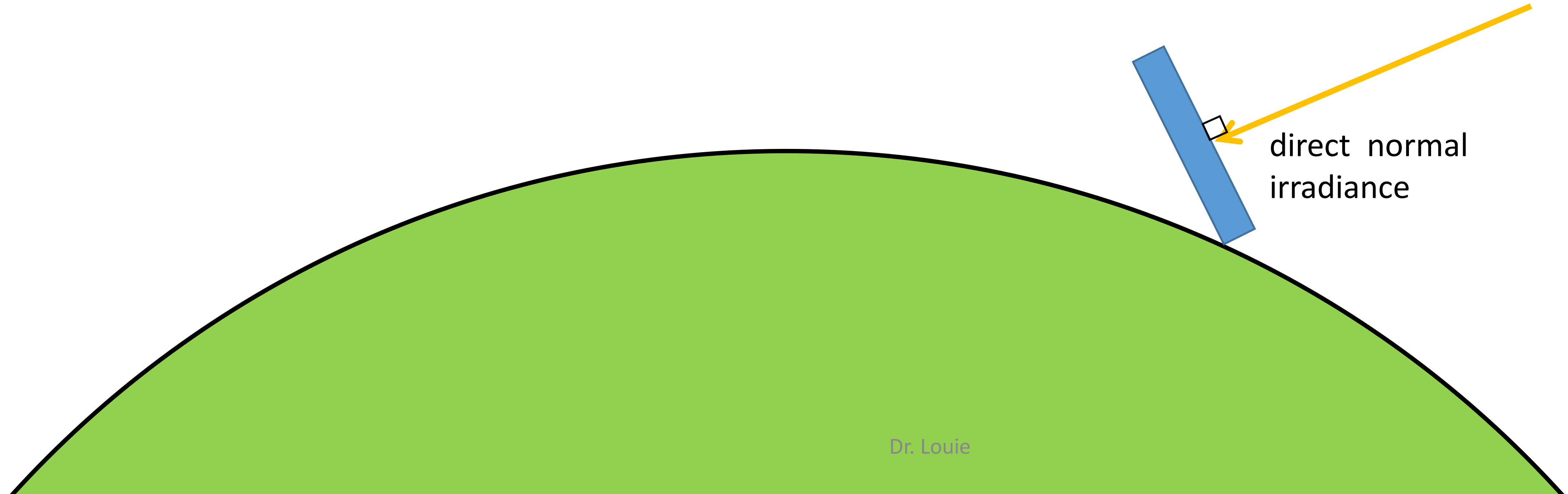
Concentrating Solar Power (CSP)

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



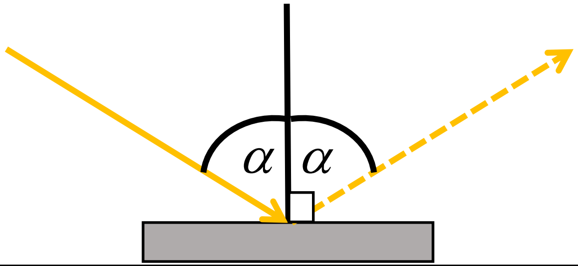
Direct Normal Irradiance

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



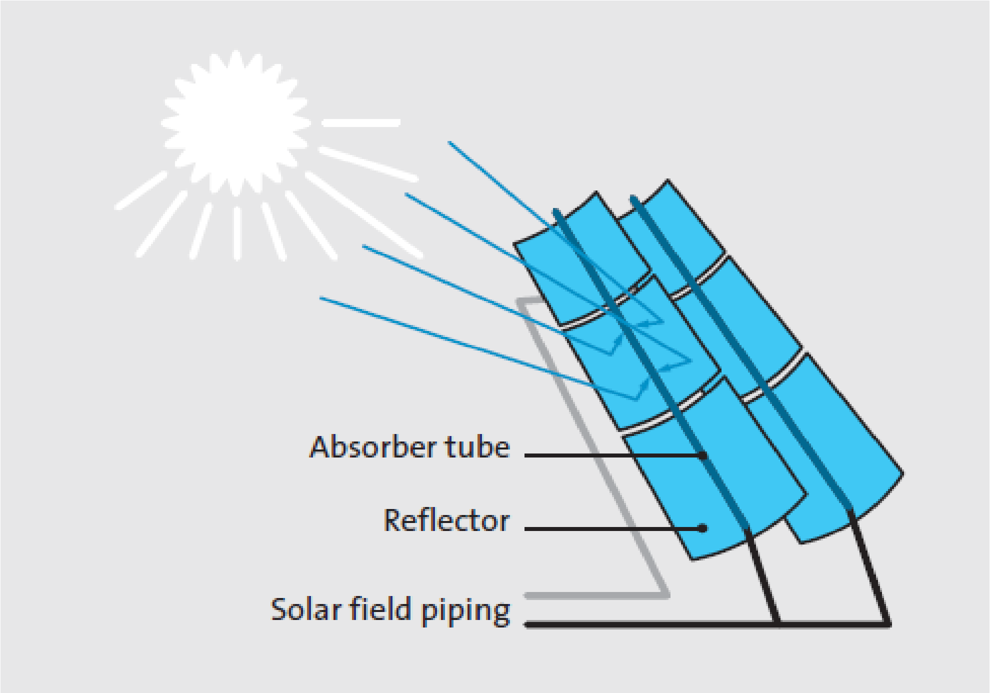
Concentrating Solar Power (CSP)

- 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?

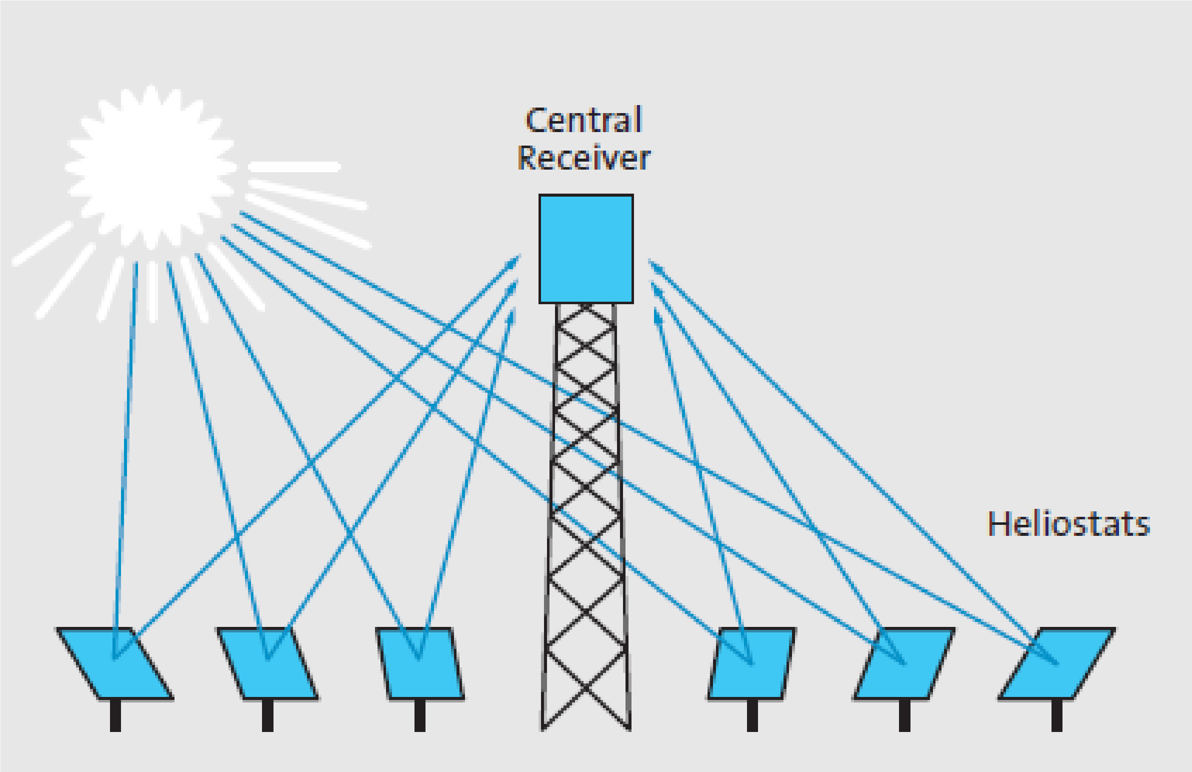
Types of CSP

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

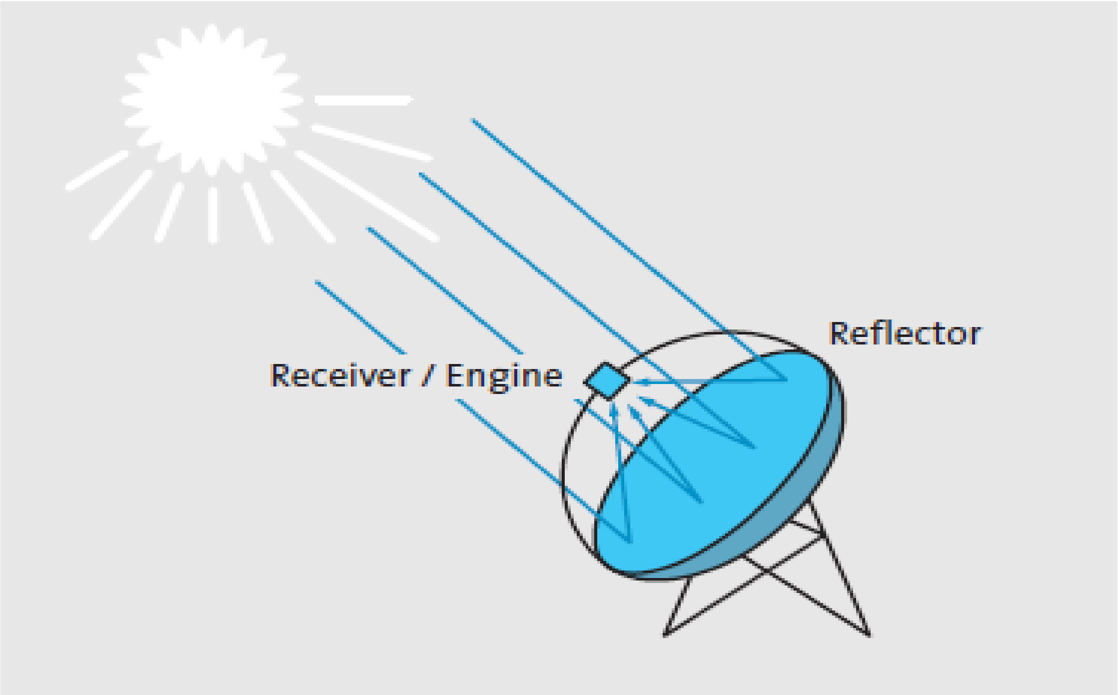
PTC



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/m^2 on a receiver that is 5m x 5m. Find the:
  - geometric concentration ratio
  - irradiation received by the receiver

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

$$\text{irradiance} = 100 \times 1000 = 100kW / m^2$$

$$\text{irradiation} = 100 \times 25 = 2.5MW$$

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

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

Concentration Ratio

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

Concentration Ratio

- What is the irradiance on the receiver?

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

- 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

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

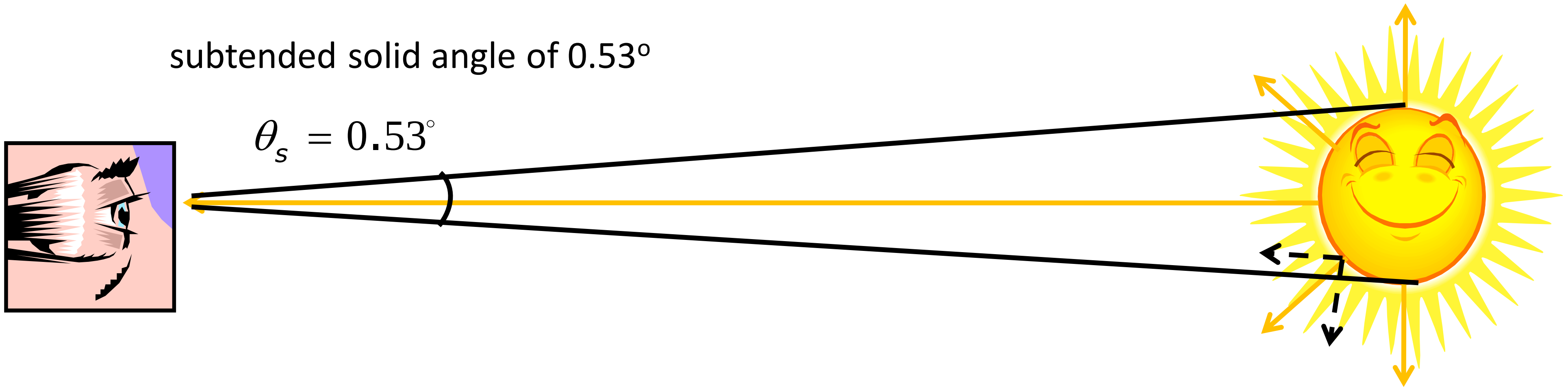
  - R: mean distance from the Earth to the Sun
  - r: radius of the Sun

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°

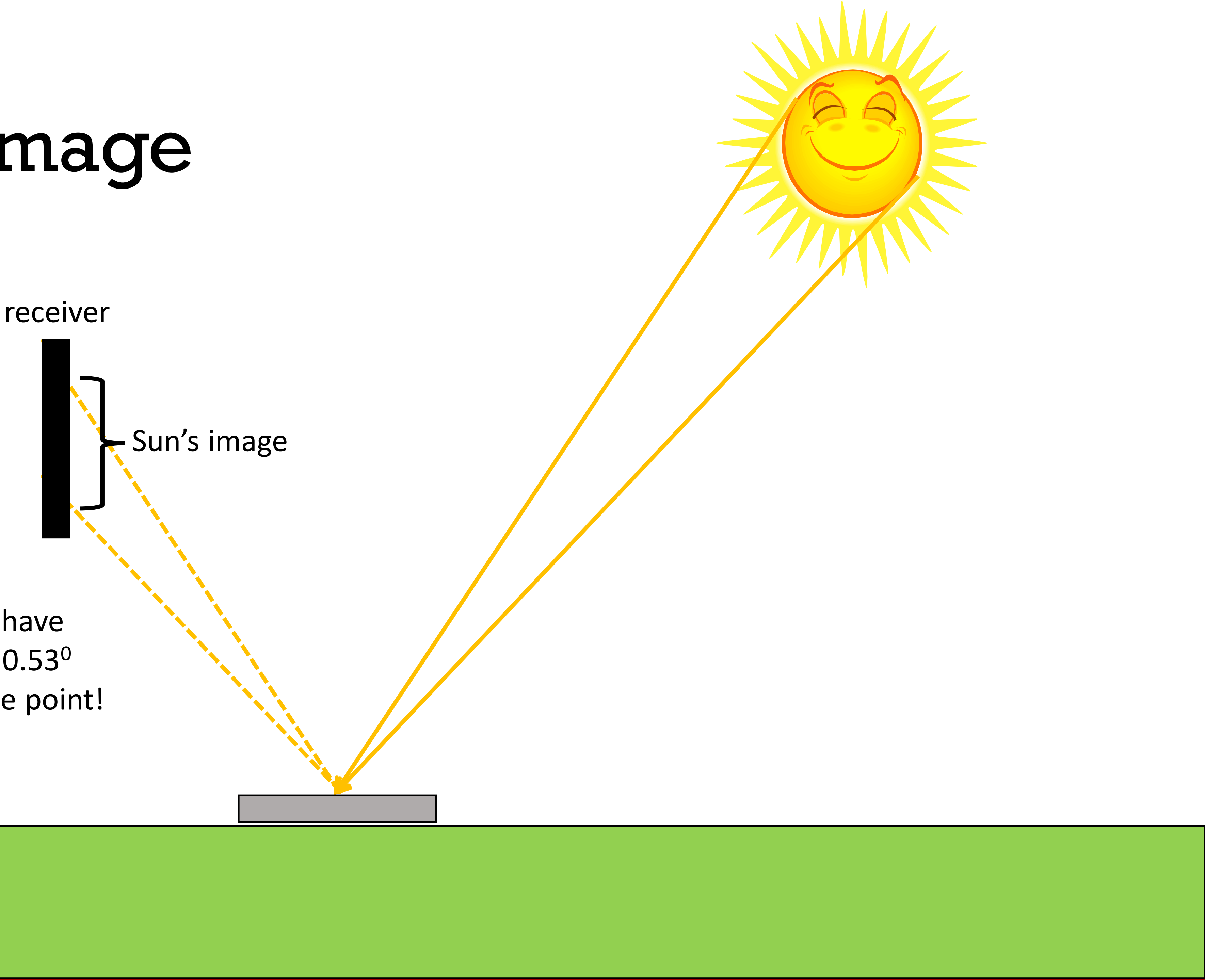


Side Note

- 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 0.53^0
Sun’s rays cannot be focused to a single point!

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:

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

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

- 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 at the receiver (to be used as input to the thermodynamic cycle):

$$\dot{Q} = A_{rec}(G_C - G_{rec}) \text{ Watts}$$

$$\dot{Q} = A_{rec}(\alpha C G_{DNI} - \sigma\varepsilon(T_{rec}^4 - T_{amb}^4)) \text{ Watts}$$

- Receiver efficiency:

$$\eta_{rec} = \dot{Q} / A_{rec} C G_{DNI}$$

CSP Efficiency

- Efficiency:

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

- 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?

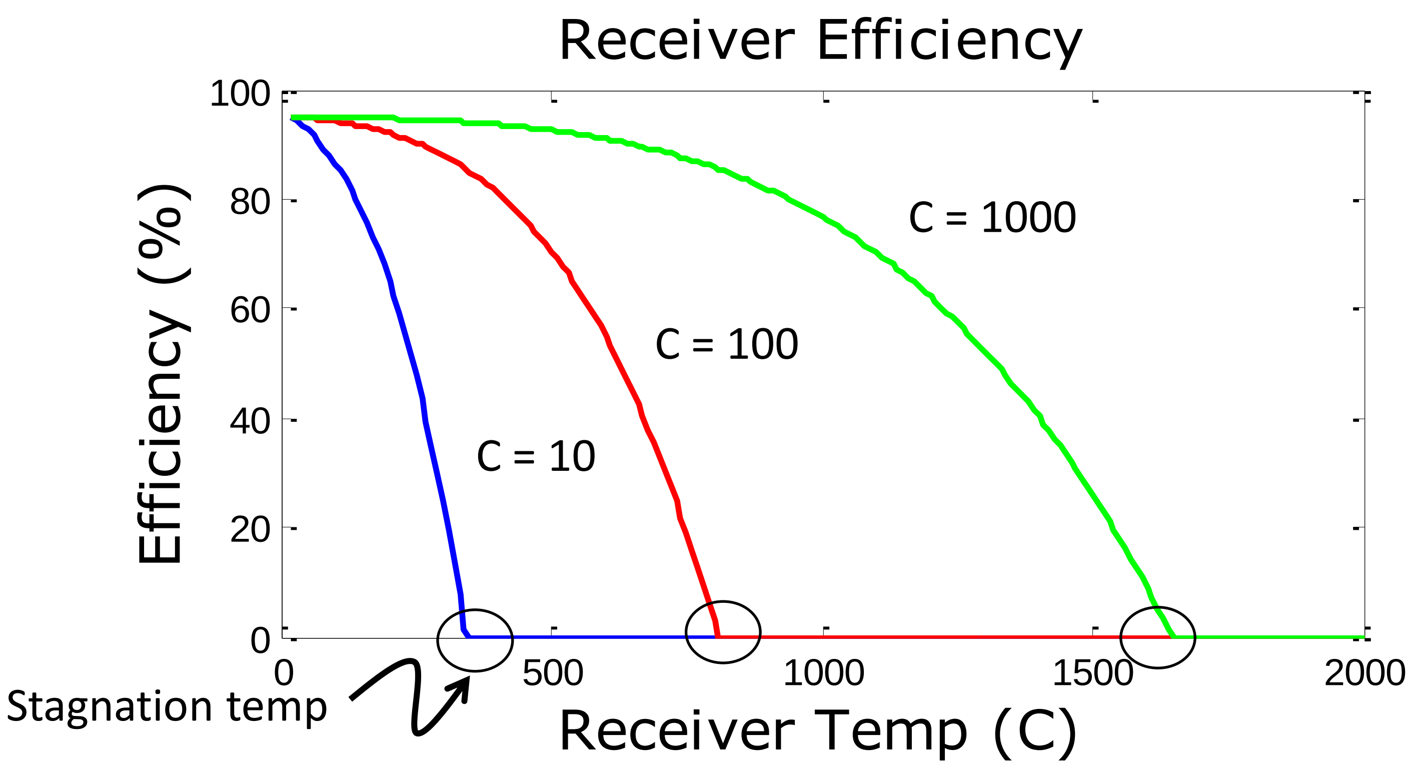
CSP Efficiency

- Efficiency:

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

- 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/m^2

CSP Efficiency

- CSPs use heat engines
- System efficiency:

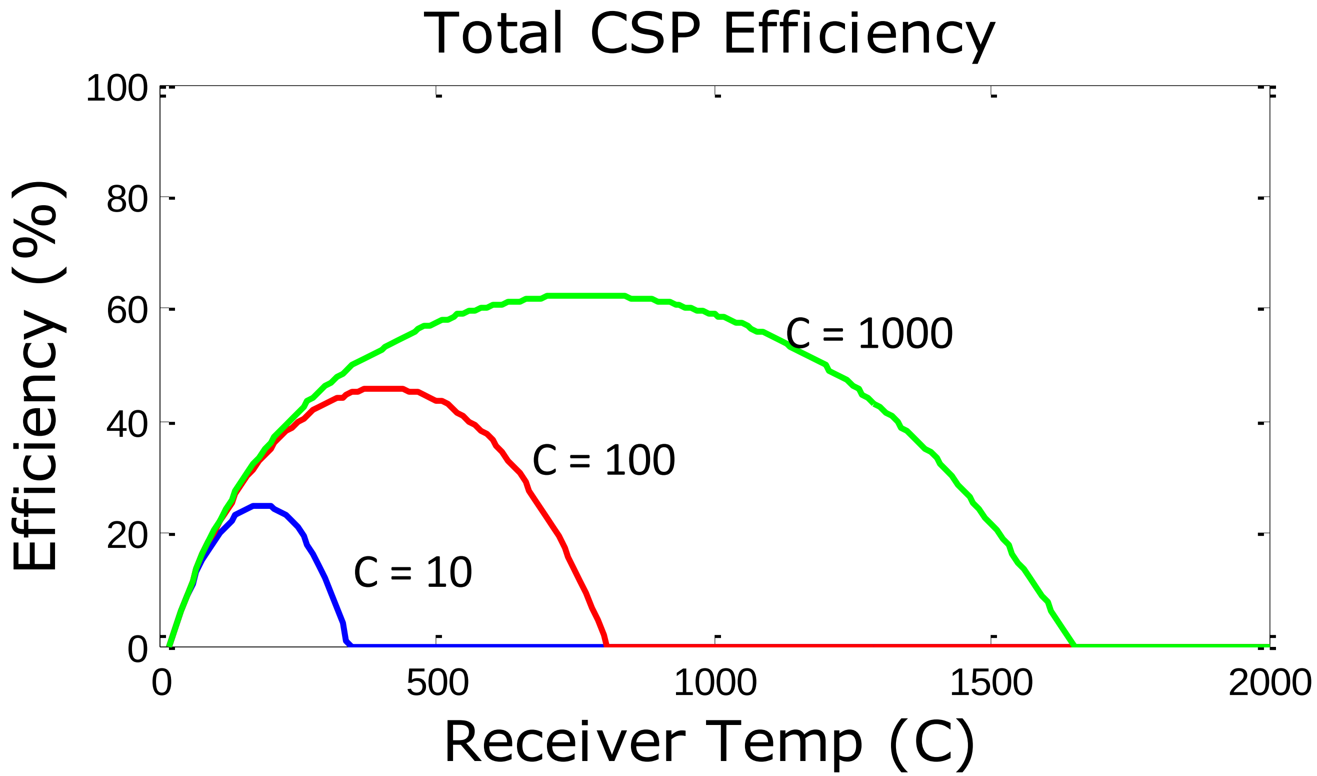
$$\eta_{CSP} = \eta_C \eta_{rec}$$

- Carnot efficiency increases with temperature

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

- Which efficiency dominates?

CSP Efficiency



Exercise

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

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

  G_{DNI} =800 W/m^2

Exercise

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

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

  G_{DNI} =800 W/m^2

- Receiver efficiency:

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

Exercise

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

  T_{rec} = 400 °C, T_{amb} = 20 °C; ε = α = 1;

  G_{DNI} =800 W/m²

- Receiver efficiency:

$$\eta_{rec} = \left(\alpha - \sigma\varepsilon \frac{(T_{rec}^4 - T_{amb}^4)}{CG_{DNI}} \right) = \left(1 - \sigma \frac{(673^4 - 293^4)}{70 \times 800} \right) \approx 80\%$$

Exercise

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

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

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

- Carnot efficiency:

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

Exercise

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

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

  G_{DNI} =800 W/m^2

- Carnot efficiency:

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

Exercise

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

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

  G_{DNI} =800 W/m^2

- Total efficiency:

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

Exercise

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

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

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

- Total efficiency:

  $\eta_{CSP} = \eta_C \eta_{rec} \approx 44.8\%$

CSP Efficiency