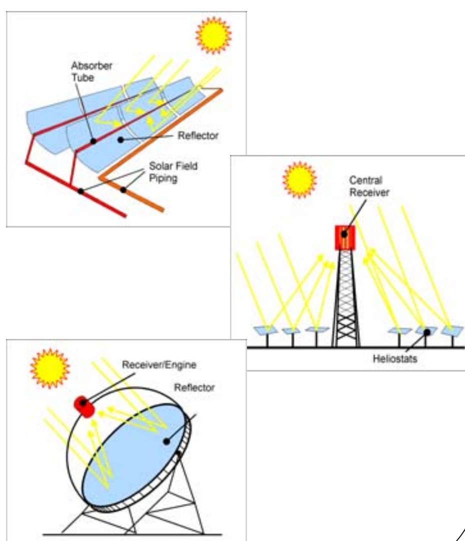
Fundamentals of Solar Thermochemical Processes

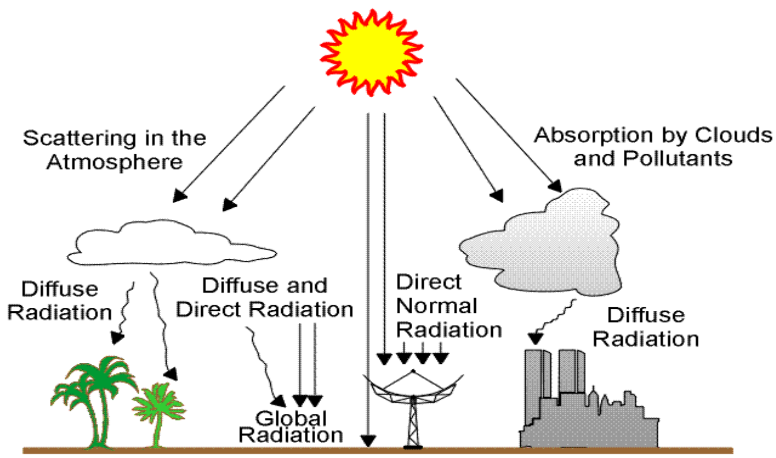
Prof. Aldo Steinfeld
ETH Zurich
Department of Mechanical and Process Engineering
ETH-Zentrum ML-J42.1
8092 Zurich
Switzerland
Tel: +41-44-632-7929
E-mail: aldo.steinfeld@ethz.ch

Solar Concentrating Technologies

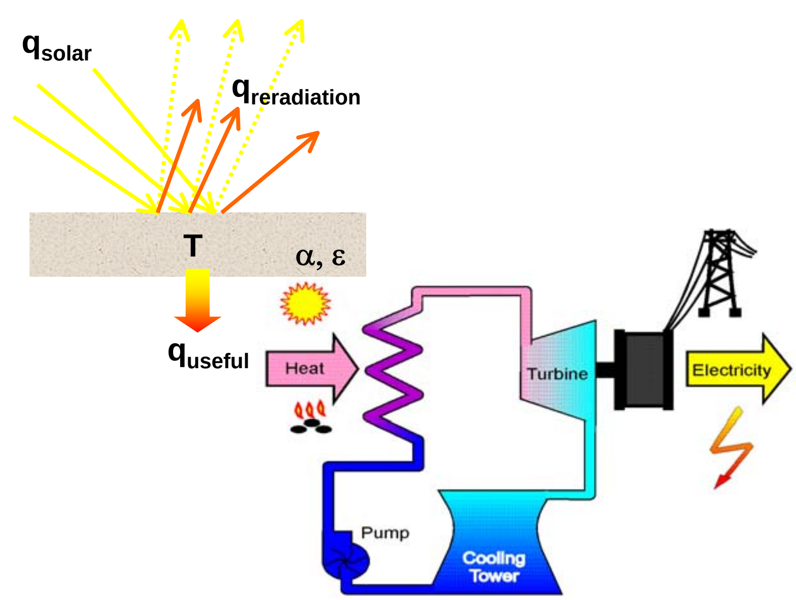
- Trough systems
- Tower systems
- Dish systems



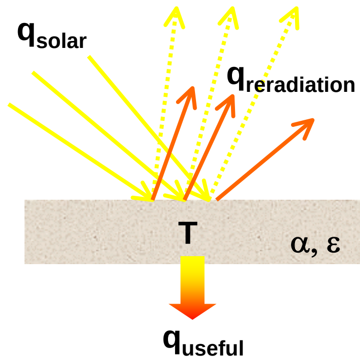
Solar Radiation



Why Concentrated Solar Energy?



Why Concentrated Solar Energy?



For:
I = 1 kW/m² (1 sun)
σ = 5.67·10⁻⁸ W/m²K⁴

C	$T_{stagnation}$
1	364 K
10	648 K
100	1152
1000	2049 K
5000	3064 K
10000	3644 K

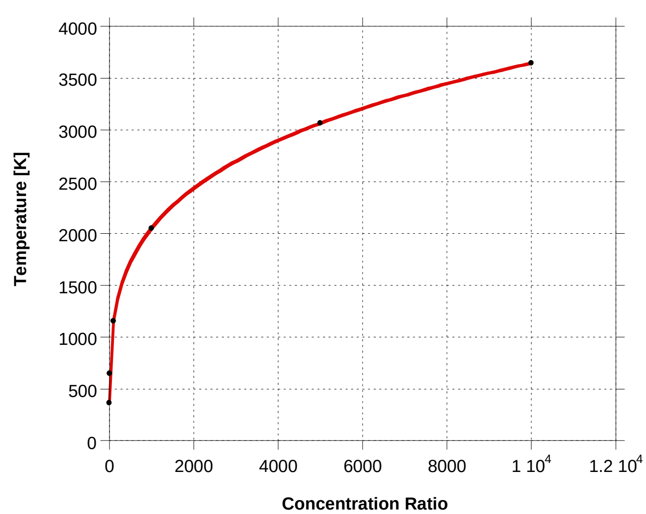
Thermal equilibrium:

$$q_{useful} = q_{absorbed} - q_{reradiation} = \alpha q_{solar} - \varepsilon\sigma T^4$$

σ = Stefan-Boltzmann constant $= 5.67051 \times 10^{-8}\ W/(m^2 \cdot K^4)$

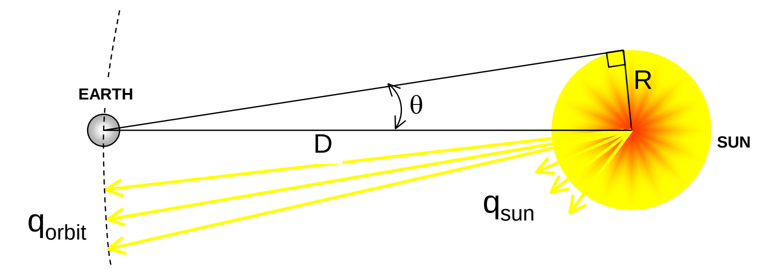
$$\text{For } q_{useful} = 0 \xrightarrow[q_{solar} = C \cdot I]{\alpha = \varepsilon = 1} T_{stagnation} = \left(\frac{C \cdot I}{\sigma}\right)^{0.25}$$

Why Concentrated Solar Energy?



C	$T_{stagnation}$
1	364 K
10	648 K
100	1152
1000	2049 K
5000	3064 K
10000	3644 K

Maximum Solar Concentration



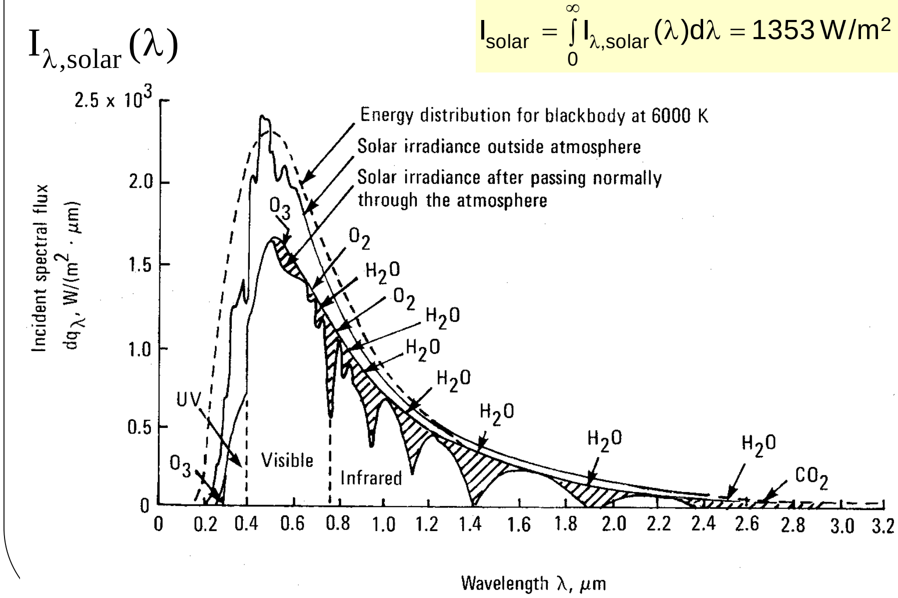
$$\left.\begin{array}{l} R = 6.9599 \cdot 10^{8}\ \text{m} \\ D = 1.505 \cdot 10^{11}\ \text{m} \end{array}\right\} \rightarrow \theta = \sin^{-1}(R/D) = 16' = 4.65\ \text{mrad}$$

$$q_{sun} \cdot 4\pi R^2 = q_{orbit} \cdot 4\pi D^2 \rightarrow \frac{q_{sun}}{q_{orbit}} = \left(\frac{D}{R}\right)^2 = \frac{1}{\sin^2\theta} \approx 46{,}200$$

$$\left.\begin{array}{l} q_{sun} = \sigma T_{sun}^4 \\ q_{orbit} = 1353\ \text{W/m}^2 \end{array}\right\} \rightarrow T_{sun} = \left[\left(\frac{D}{R}\right)^2 \frac{q_{orbit}}{\sigma}\right]^{0.25} = 5780\ \text{K}$$

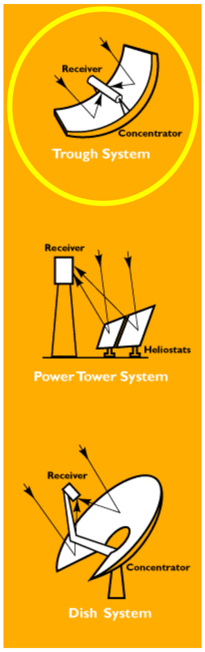
Solar Radiation

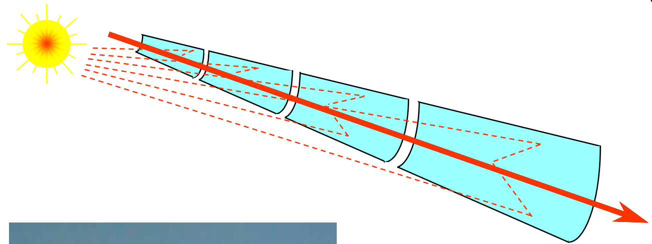
$$I_{solar} = \int_0^\infty I_{\lambda,solar}(\lambda)\, d\lambda = 1353\ \text{W/m}^2$$



ETH — PSI

Parabolic Trough System

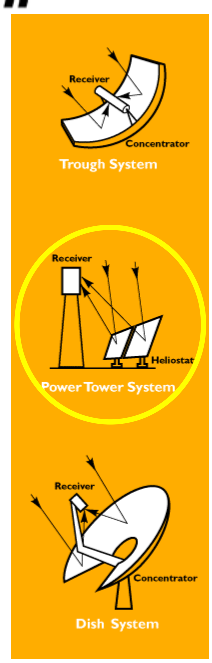


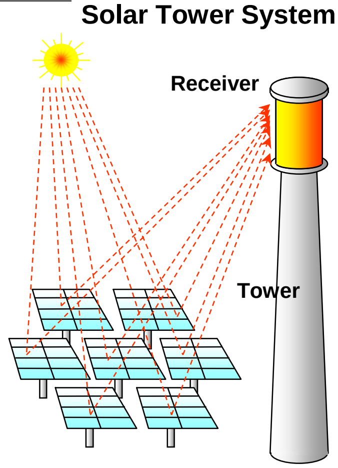


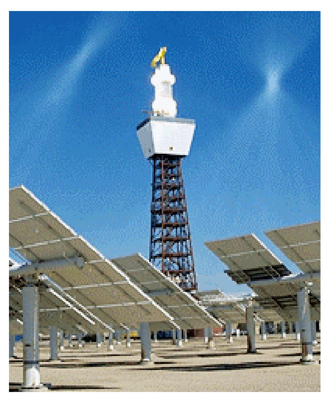
- Line focusing.
- C = 30 - 80.
- Unit 30 - 80 MW.
- Unidirectional trough curvature.
- 1-axis tracking N-S.

ETH — PSI

Solar Tower System



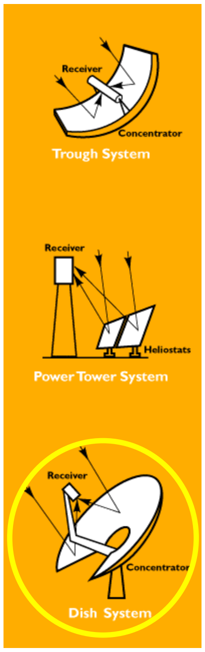


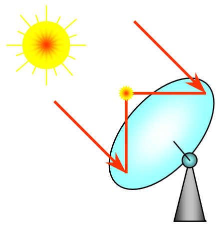


Heliostat Field

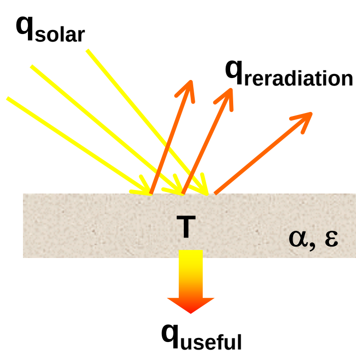
- Point focusing.
- C = 200 - 1000.
- Unit 30 - 200 MW.
- 2-axis tracking heliostats: elements of different parabolas with varying focal length.

Solar Dish System





- Point focusing.
- C = 1000 - 13,000.
- Unit 7.5 - 100 kW.
- 2-axis tracking parabolic dish.
- Modularity.
- Remote applications.



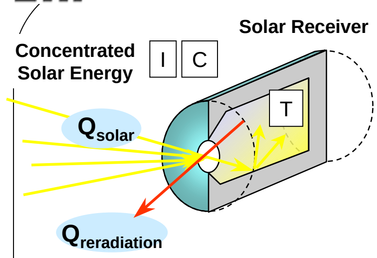
In thermal equilibrium:

$$q_{useful} = q_{absorbed} - q_{reradiation}$$

$$q_{useful} = \alpha q_{solar} - \varepsilon\sigma T^4$$

$$Q_{useful} = \alpha Q_{solar} - \varepsilon A\sigma T^4$$

ETH



$$\eta_{absorption} = \frac{\overbrace{[\ \alpha\, Q_{solar}\ ]}^{\text{Power absorbed}} - \overbrace{[\ \varepsilon\, A\, \sigma T^4\ ]}^{\text{Power re-radiated}}}{\underbrace{[\ Q_{solar}\ ]}_{\text{Solar Power Input}}}$$

$$\left.\begin{array}{l}\alpha = \varepsilon = 1 \\ C = \dfrac{Q_{solar}}{A \cdot I}\end{array}\right\} \Rightarrow \eta_{absorption} = \left(1 - \frac{\sigma T^4}{C \cdot I}\right)$$

$$\eta_{exergy,ideal} = \eta_{absorption} \cdot \eta_{Carnot} = \left(1 - \frac{\sigma T^4}{C \cdot I}\right) \cdot \left(1 - \frac{T_L}{T}\right)$$

ETH PSI

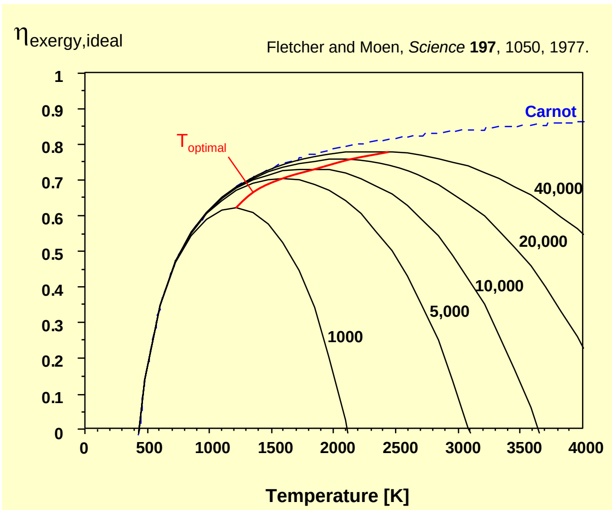
$$\eta_{exergy,ideal} = \eta_{absorption} \cdot \eta_{Carnot} = \left(1 - \frac{\sigma T^4}{C \cdot I}\right) \cdot \left(1 - \frac{T_L}{T}\right)$$

$$\eta_{exergy} = 0 \rightarrow T_{stagnation} = \left(\frac{C \cdot I}{\sigma}\right)^{0.25}$$

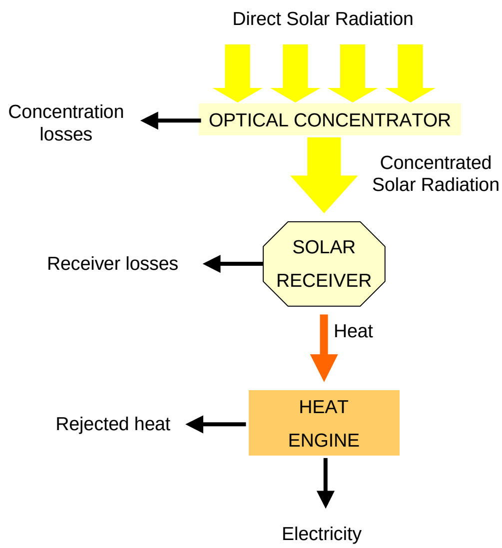
$$\frac{\partial \eta_{exergy}}{\partial T} = 0 \rightarrow \left(T_{optimal}\right)^5 - 0.75 T_L \left(T_{optimal}\right)^4 - \left(\frac{T_L I C}{4\sigma}\right) = 0$$

For:
$I = 1$ kW/m^2 (1 sun)
$\sigma = 5.67 \cdot 10^{-8}$ W/m^{2}K^4

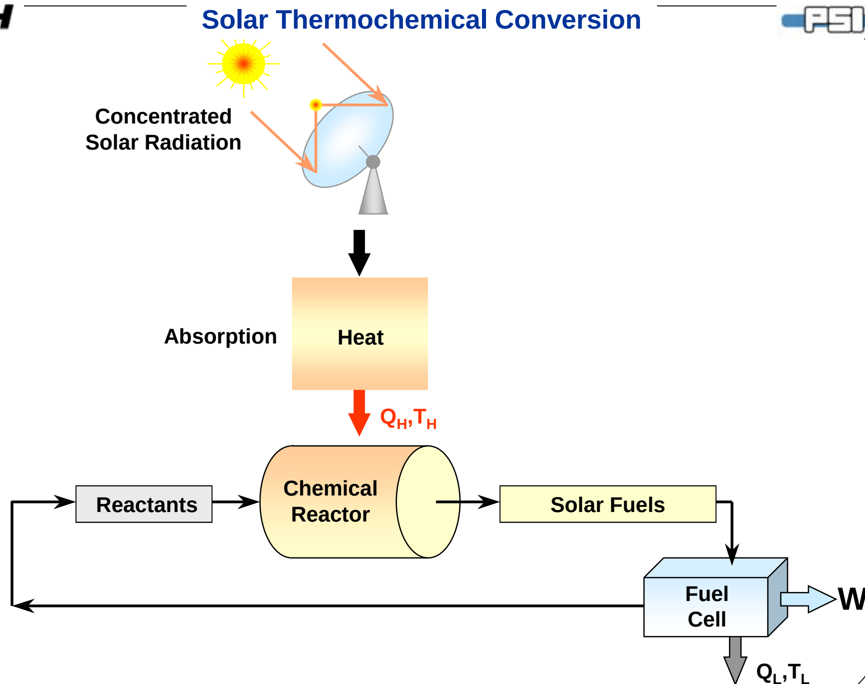
C	$T_{stagnation}$	$T_{optimal}$
1000	2049 K	1106 K
5000	3064 K	1507 K
10000	3644 K	1724 K

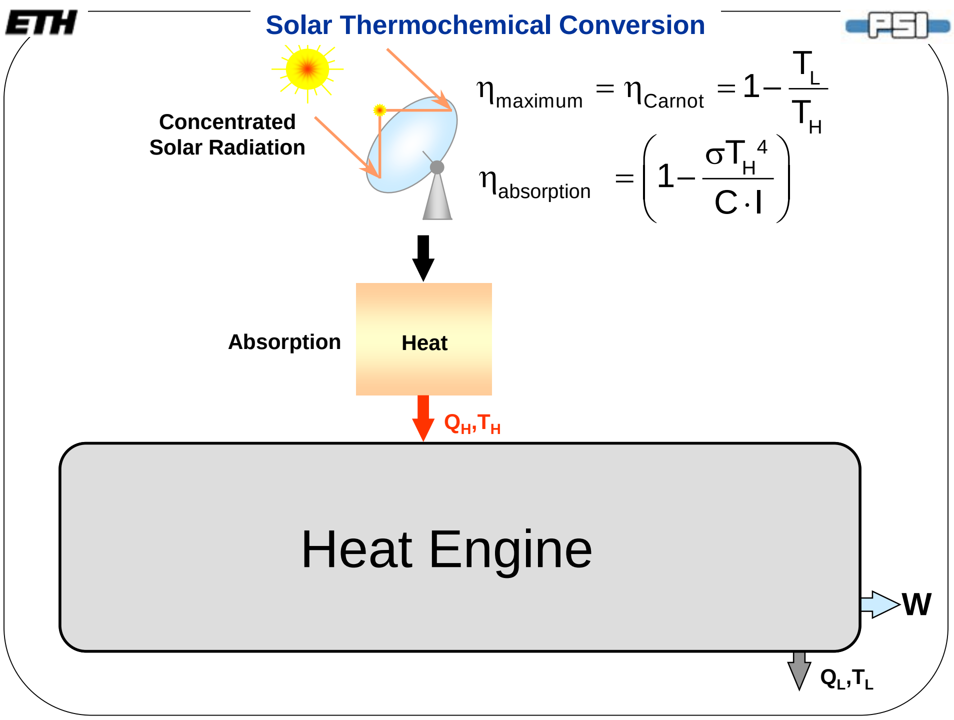


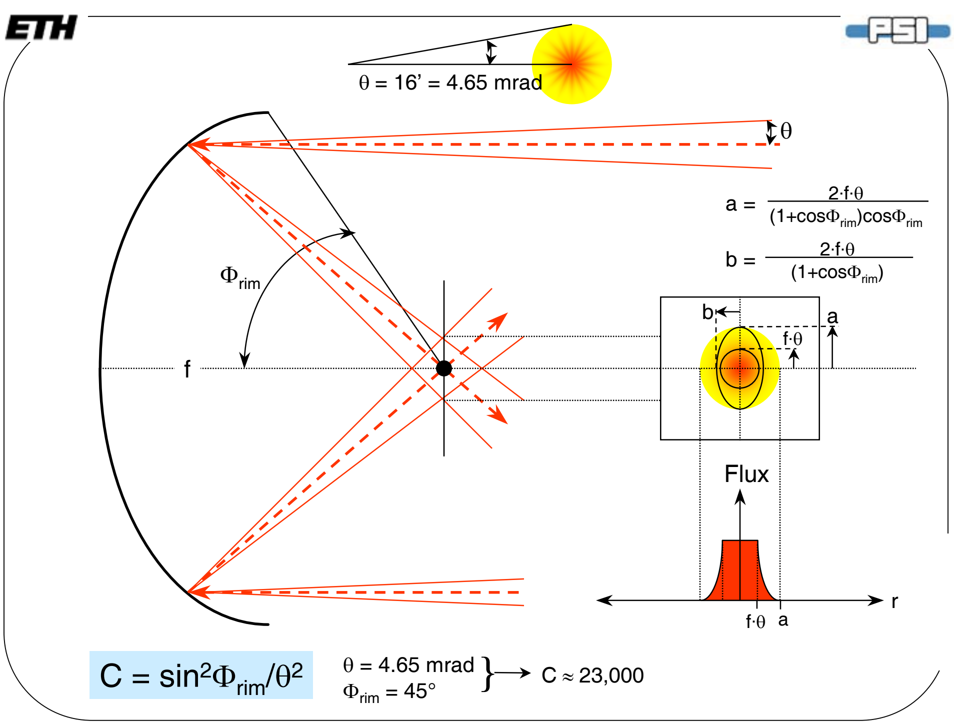
$$\eta_{solar-to-electrcity} = \eta_{optics} \cdot \underbrace{\eta_{receiver}}_{<\eta_{absorption}} \cdot \underbrace{\eta_{heat-to-electricity}}_{<\eta_{Carnot}}$$



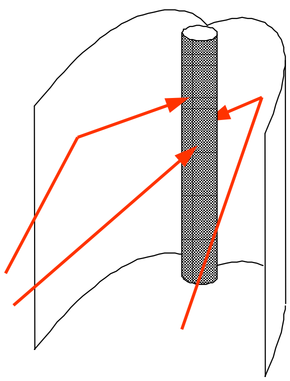
Solar Thermochemical Conversion



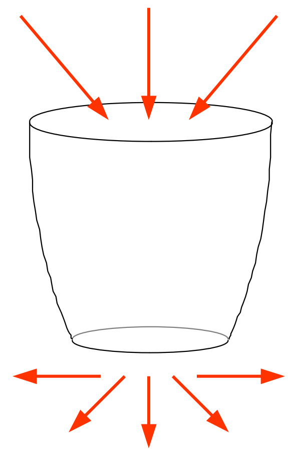

ETH
Solar Thermochemical Conversion
PSI
Concentrated Solar Radiation
$\eta_{maximum} = \eta_{Carnot} = 1 - \frac{T_L}{T_H}$
$\eta_{absorption} = \left(1 - \frac{\sigma T_H^4}{C \cdot I}\right)$
Absorption
Heat
Q_H, T_H
Heat Engine
W
Q_L, T_L


ETH
PSI
θ = 16' = 4.65 mrad
θ
$a = \frac{2 \cdot f \cdot \theta}{(1+\cos\Phi_{rim})\cos\Phi_{rim}}$
$b = \frac{2 \cdot f \cdot \theta}{(1+\cos\Phi_{rim})}$
Φ_{rim}
f
b
a
f·θ
Flux
r
f·θ
a
$C = \sin^2\Phi_{rim}/\theta^2$
θ = 4.65 mrad
Φ_{rim} = 45°
C ≈ 23,000

CPC – Compound Parabolic Concentrator

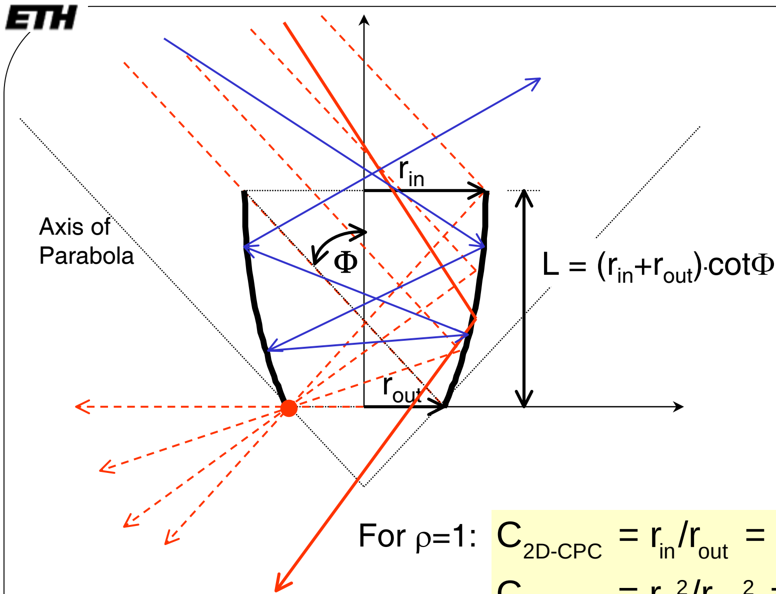


2D - CPC



3D - CPC

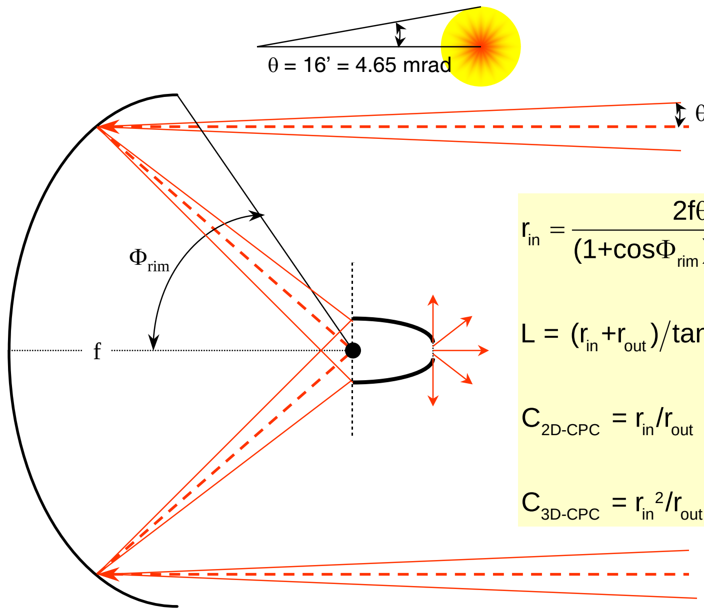
Ref.: Welford, W. T., and Winston, R. (1989). *High Collection Nonimaging Optics* Academic Press, San Diego, USA.



For ρ=1:

$$C_{2D\text{-}CPC} = r_{in}/r_{out} = 1/\sin\Phi$$

$$C_{3D\text{-}CPC} = r_{in}^2/r_{out}^2 = 1/\sin^2\Phi$$



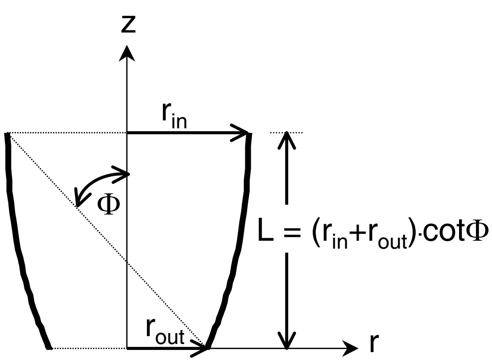
$$r_{in} = \frac{2f\theta}{(1+\cos\Phi_{rim}).\cos\Phi_{rim}}$$

$$L = (r_{in}+r_{out})/\tan\Phi_{rim}$$

$$C_{2D\text{-}CPC} = r_{in}/r_{out} = 1/\sin\Phi$$

$$C_{3D\text{-}CPC} = r_{in}^2/r_{out}^2 = 1/\sin^2\Phi$$

Equations of the CPC



$$\begin{cases} r = \dfrac{2f\sin(\varphi-\Phi)}{1-\cos\varphi} - r_{out} \\ z = \dfrac{2f\cos(\varphi-\Phi)}{1-\cos\varphi} \end{cases}$$

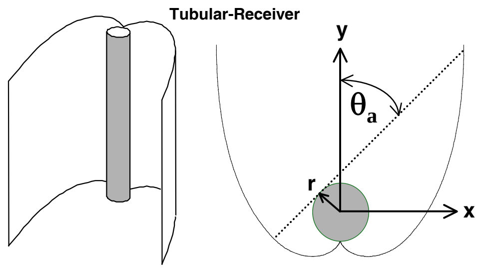
where:

$$r_{out} = r_{in}\sin\Phi$$

$$f = r_{out}(1+\sin\Phi)$$

$$2\Phi \le \varphi \le \frac{\pi}{2} + \Phi$$

Equations of the 2-D CPC + involute



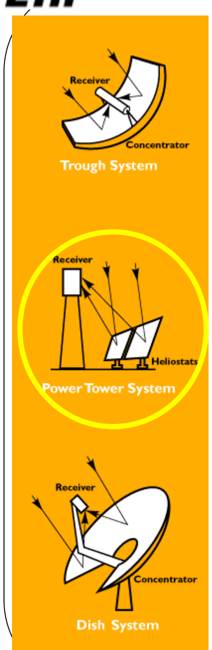
$$\begin{cases} x = r[\sin\theta - M(\theta)\cos\theta] \\ y = r[-\cos\theta - M(\theta)\sin\theta] \end{cases}$$

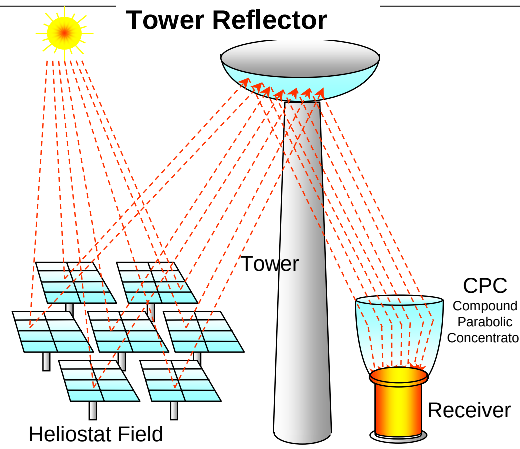
$$M(\theta) = \begin{cases} \theta & \text{for } 0 \le \theta \le \frac{\pi}{2} + \theta_a \\ \dfrac{\pi/2 + \theta_a + \theta - \cos(\theta - \theta_a)}{1 + \sin(\theta - \theta_a)} & \text{for } \frac{\pi}{2} + \theta_a \le \theta \le \frac{3\pi}{2} - \theta_a \end{cases}$$

θ_a CPC's half acceptance angle and is taken equal to the rim angle of the primary parabolic concentrator.

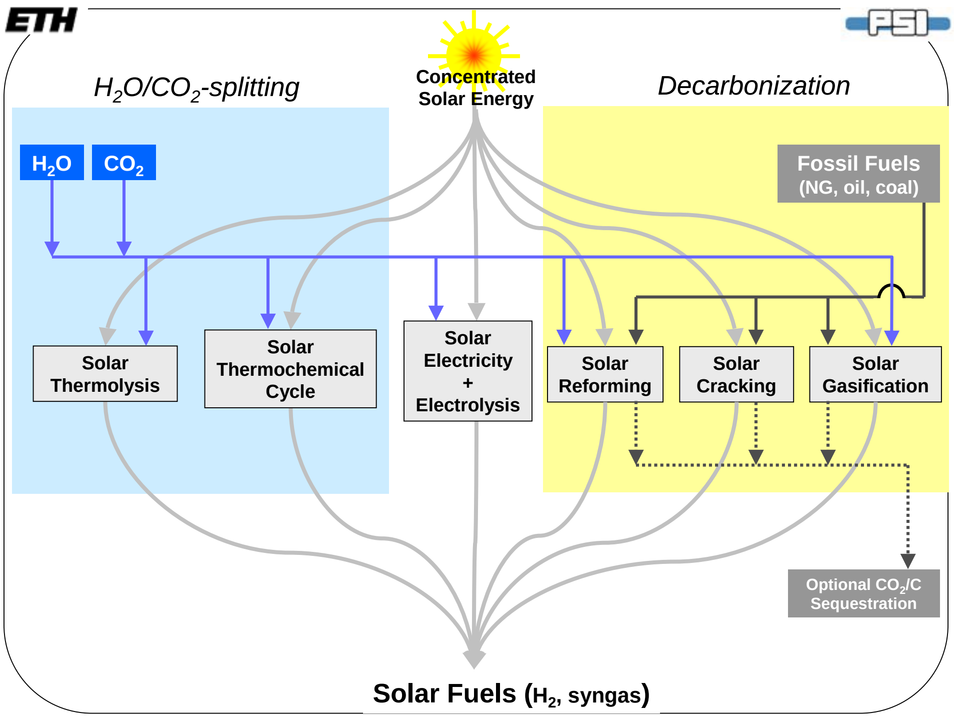
r radius tubular receiver.

Tower Reflector





- Heliostat field + Tower Reflector (Cassegrain).
- Beam-down on CPC.
- C = 5,000 - 10,000.
- Major hardware on ground level.


H2O/CO2-splitting
Concentrated Solar Energy
Decarbonization
H2O
CO2
Fossil Fuels (NG, oil, coal)
Solar Thermolysis
Solar Thermochemical Cycle
Solar Electricity + Electrolysis
Solar Reforming
Solar Cracking
Solar Gasification
Optional CO2/C Sequestration
Solar Fuels (H2, syngas)