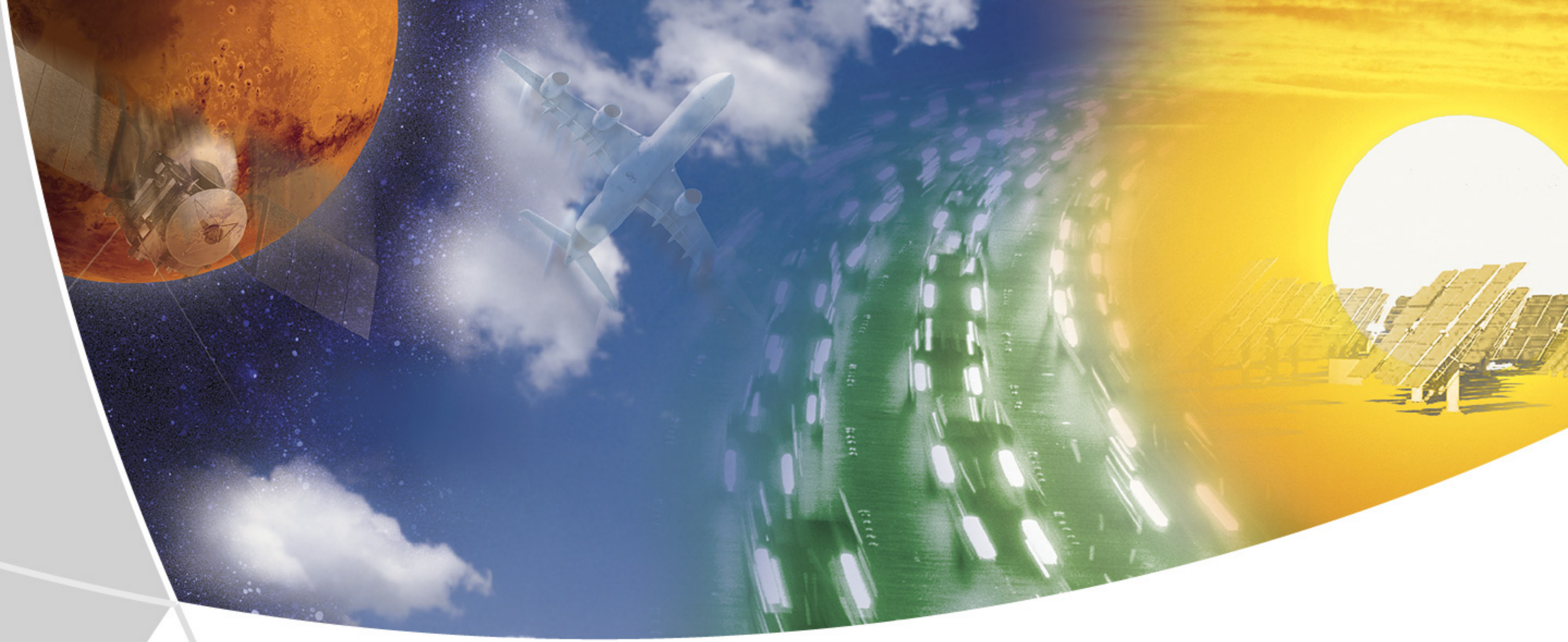


Solarthermische Kraftwerke zur Energieversorgung im Sonnengürtel

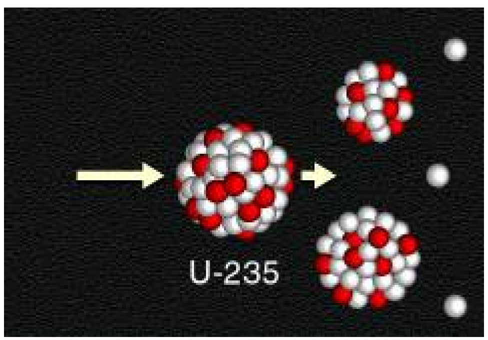
Robert Pitz-Paal

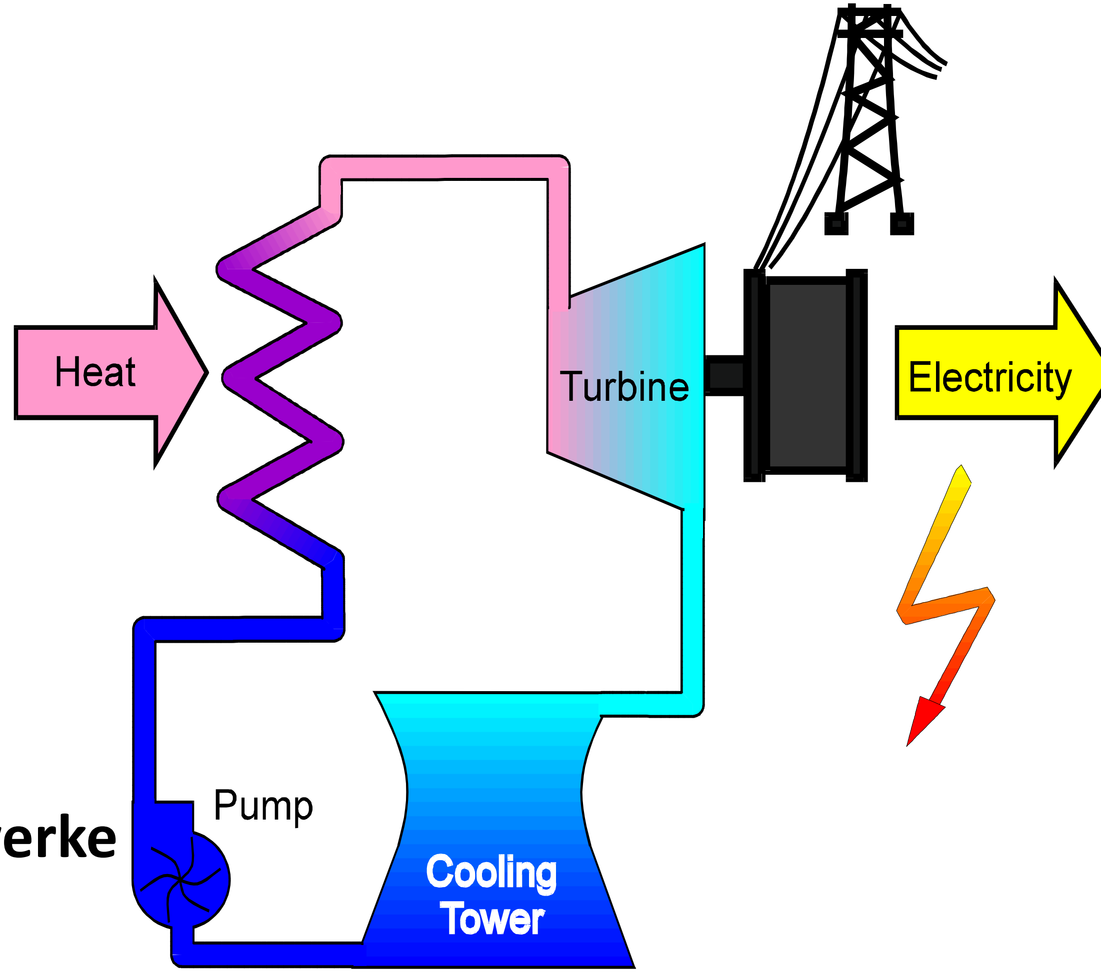
Institute of Solar Research
German Aerospace Center (DLR)

Chair Solar Technology
Aachen University

DLR Deutsches Zentrum für Luft- und Raumfahrt e.V.
in der Helmholtz-Gemeinschaft

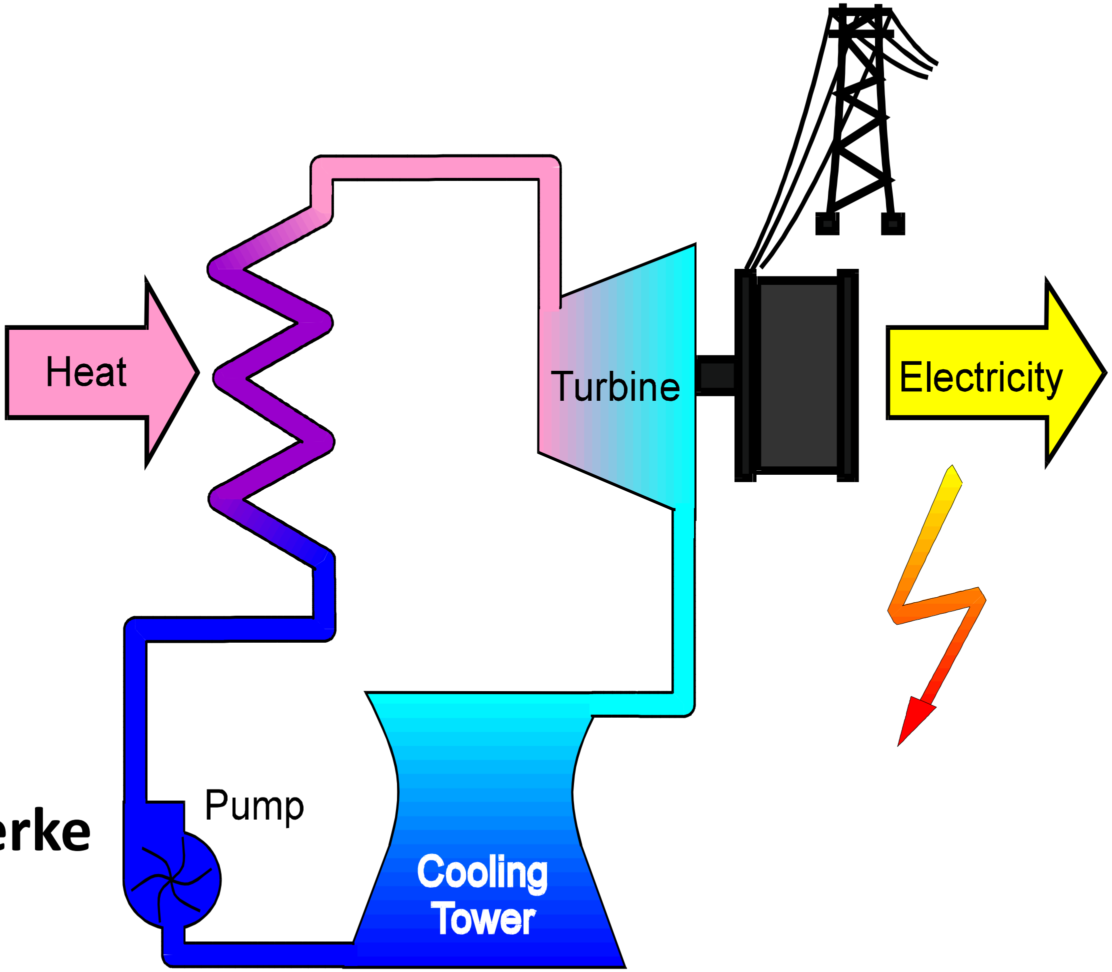
Was ist CSP?





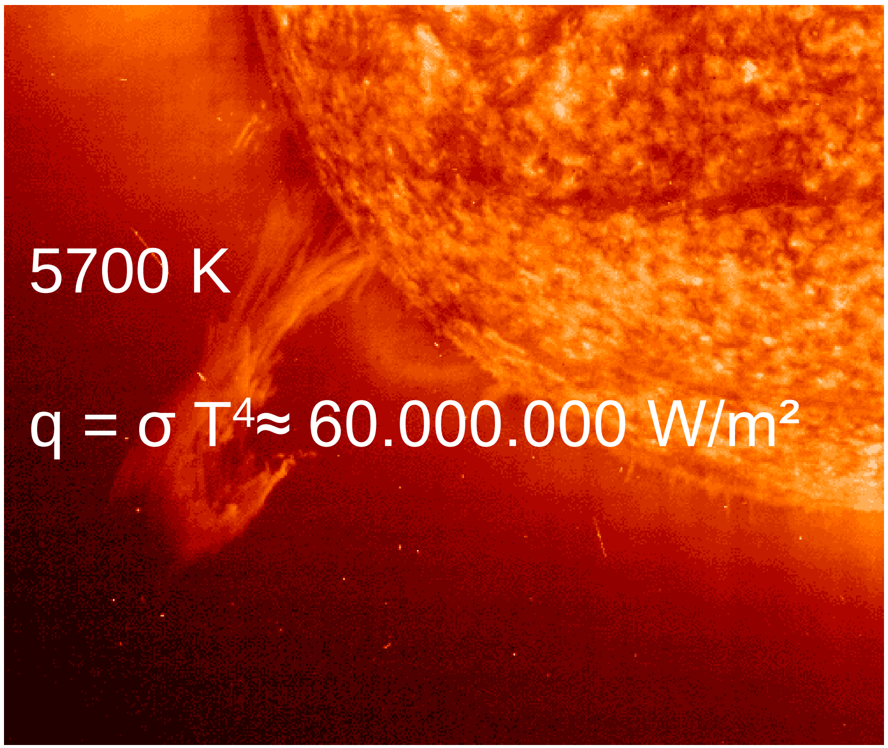
Konventionelle Kraftwerke

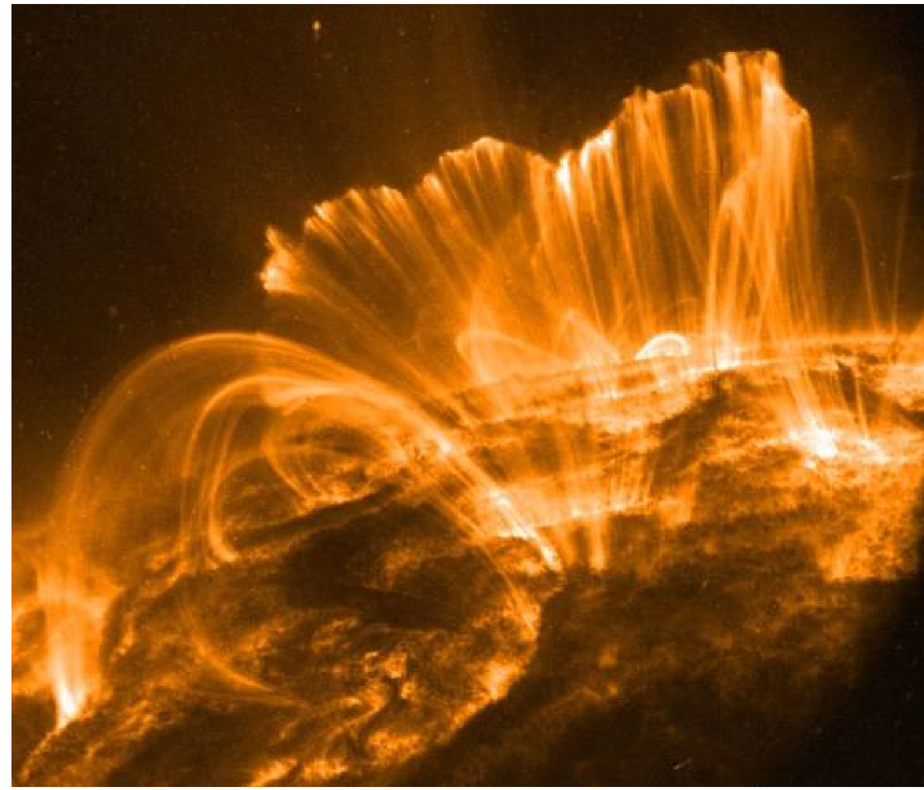
Was ist CSP?



Solarthermische Kraftwerke

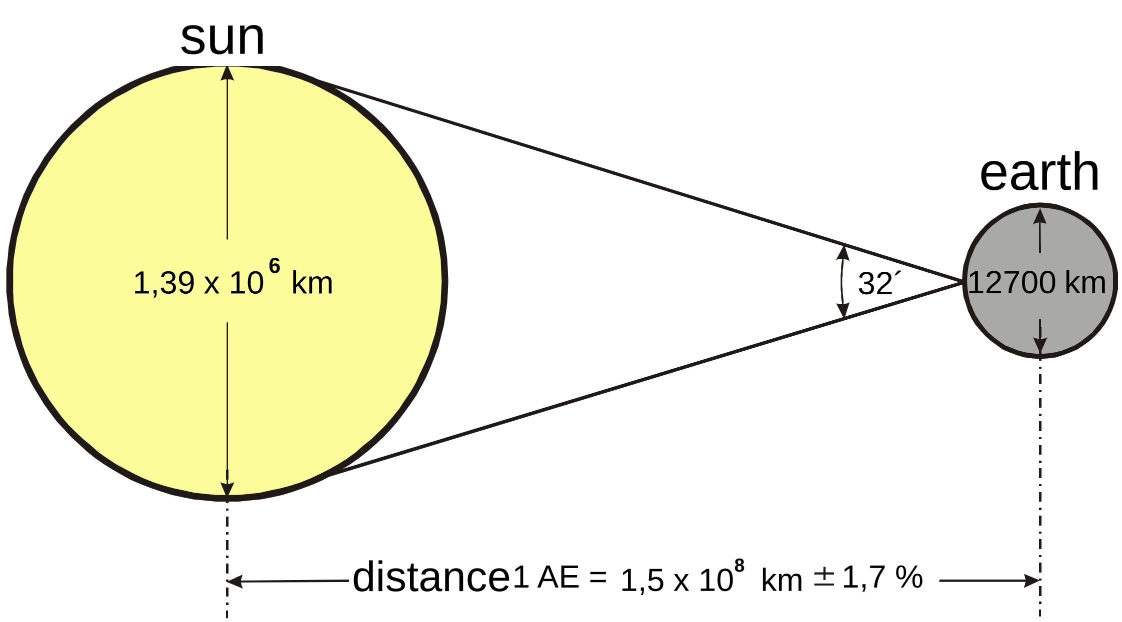
Pictures of the sun surface





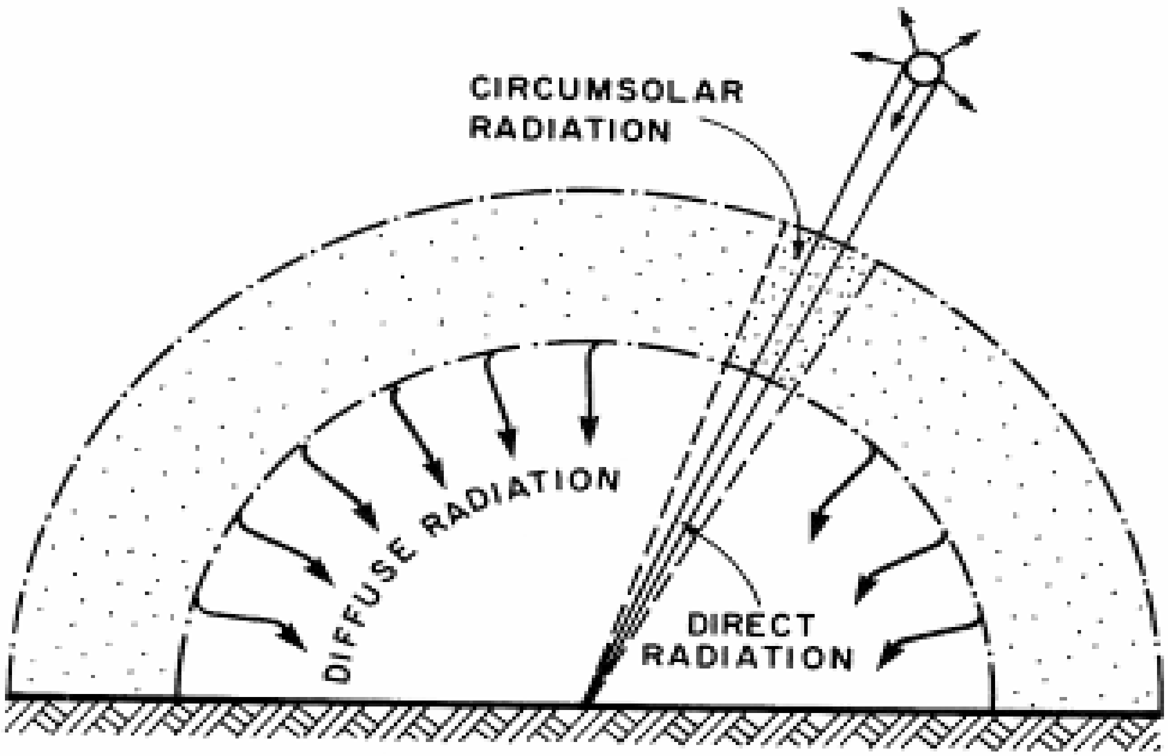
Solar constant I_o

= average energy per unit time which is radiated from the sun perpendicular to an area on the outer atmosphere of the earth.

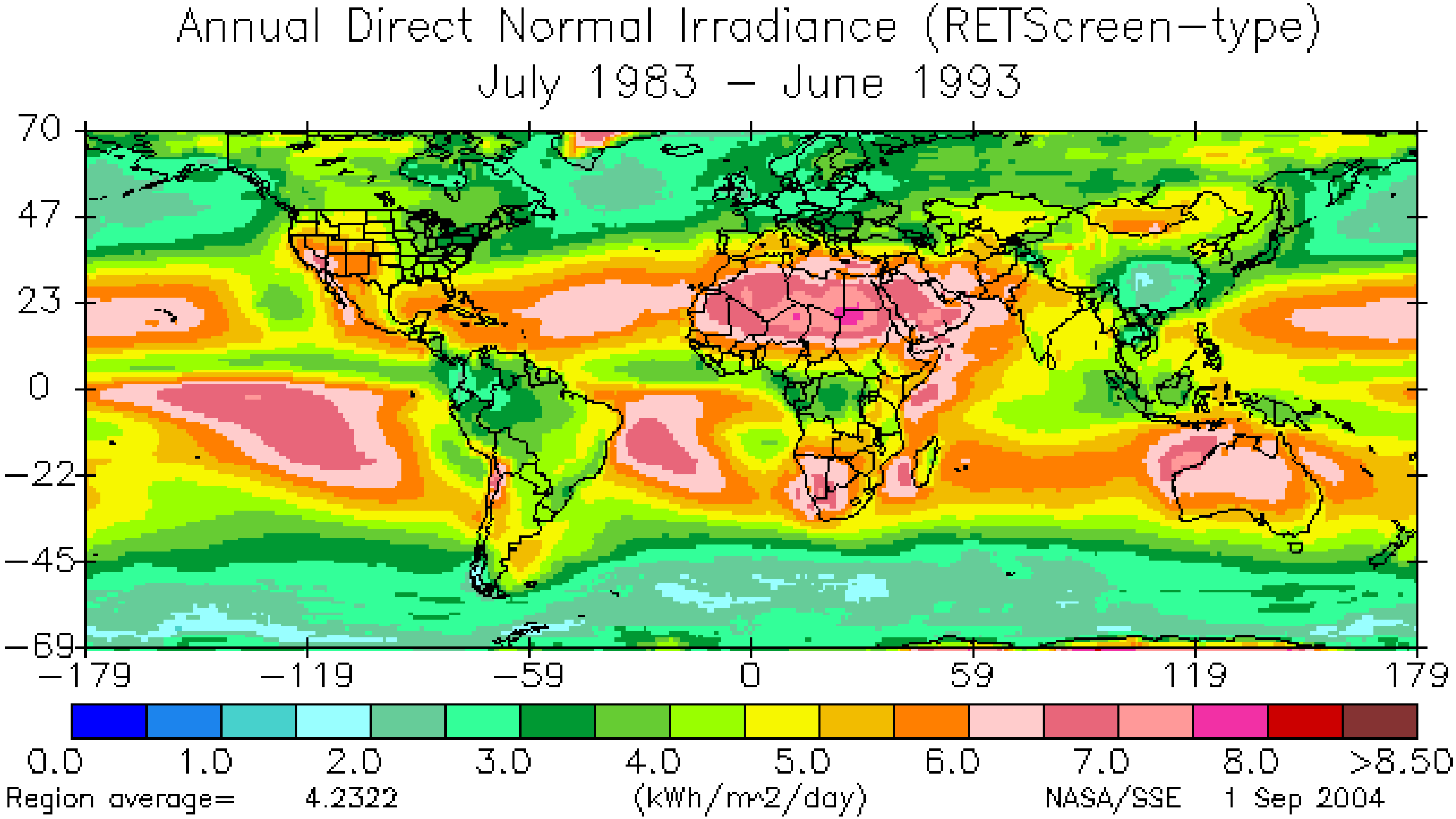


$$\frac{I_0}{I_S} = \frac{A_S}{A_{AE}} = \frac{4 \cdot \pi \cdot R_S^2}{4 \cdot \pi \cdot AE^2}, \quad I_0 = I_S \cdot \frac{R_S^2}{AE^2} = \sigma \cdot T_S^4 \cdot \frac{R_S^2}{AE^2} \approx 1360\ W/m^2 = 4870\ kJ/(m^2\,y)$$

Diffuse and direct radiation



World solar energy supply (space: 32 kWh / m^2 / day)



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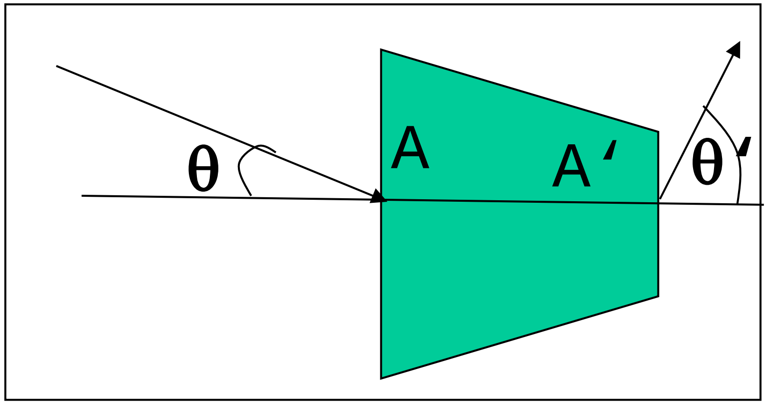
Concentration

Concentration factor C is defined as the ratio of Energy flux density E´ at the exit aperture of the concentrator to the energy flux to the Energy flux E ate the entrance aperture of the concentrator

$$C = \frac{E'}{E} = \frac{A}{A'}$$



With E = dΦ / dA [W/m^2], averaged over the aperture A resp. A´

Φ = Energy Flux [W]

θ = half cone angle

Concentration factor C

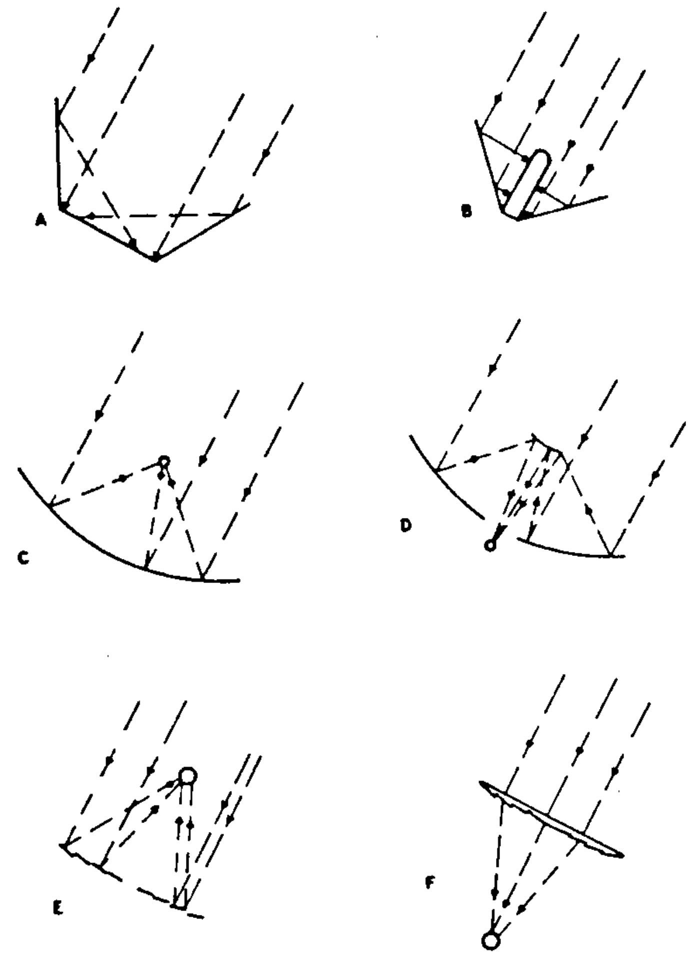
= ratio of the radiation flux density E´ after concentration to the radiation flux density E before concentration

Geometrical concentration ratio C

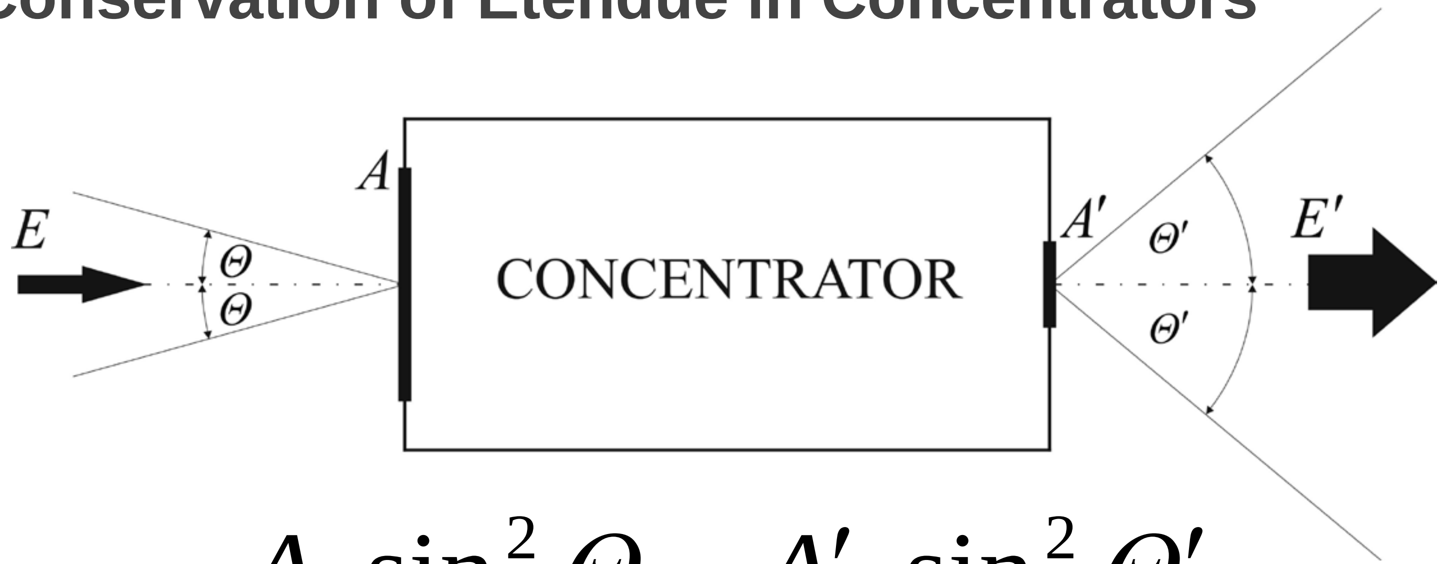
$$C = \frac{\text{aperture area}}{\text{area of sunshape in focal plain}}$$

Technical concentration if absorber ≈ focal area

$$C = \frac{\text{aperture area}}{\text{absorber area}} = \frac{A_R}{A_A}$$



Conservation of Etendue in Concentrators

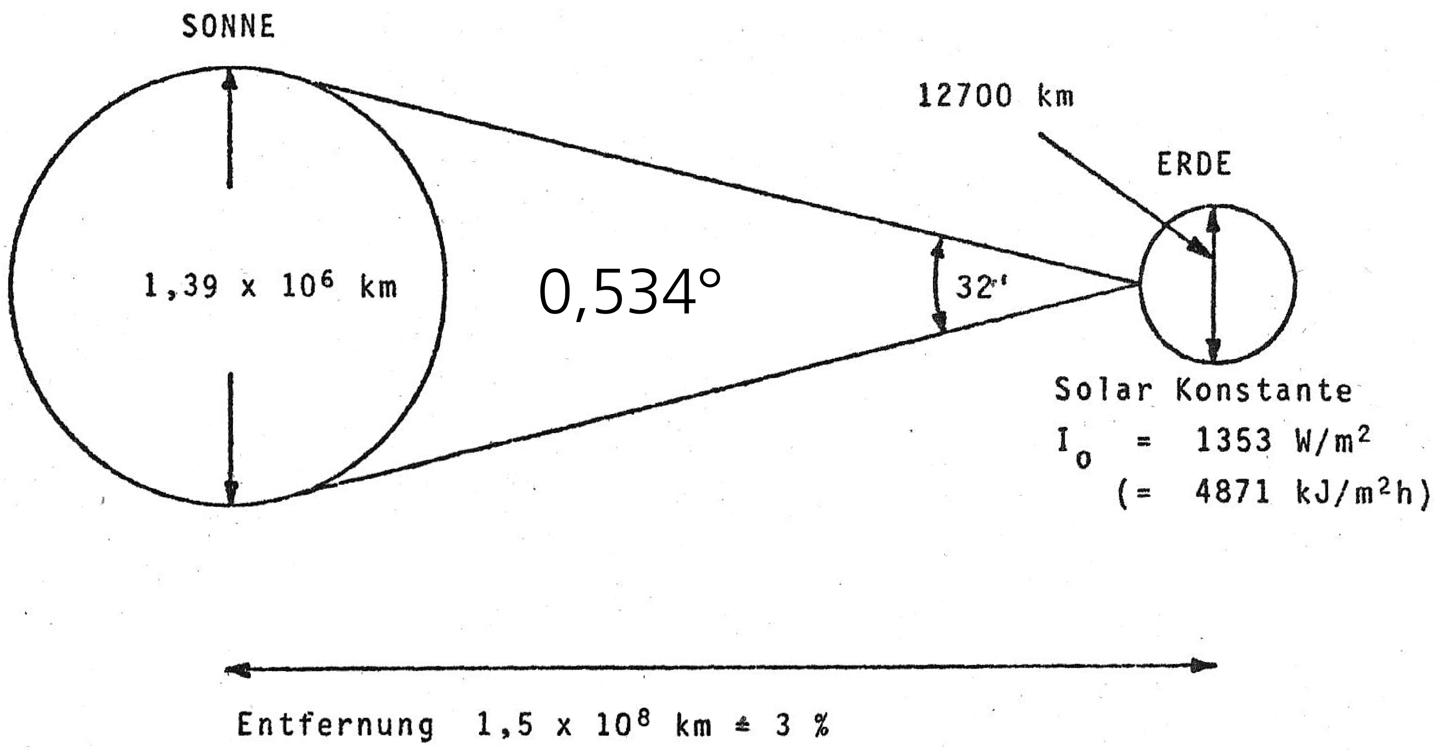


3D
$$A \cdot \sin^2 \Theta = A' \cdot \sin^2 \Theta'$$

2D
$$A \cdot \sin \Theta = A' \cdot \sin \Theta'$$

$$C_{3D} = \frac{A}{A'} = \frac{\sin^2 \Theta'}{\sin^2 \Theta} \qquad C_{2D} = \frac{A}{A'} = \frac{\sin \Theta'}{\sin \Theta}$$

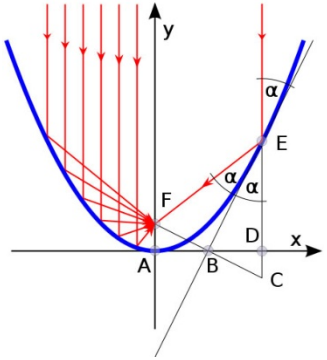
Maximum Concentration



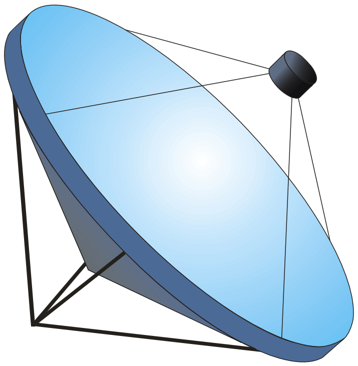
$$C_{\max,3D} = \frac{A}{A'} = \frac{\sin^2 90°}{\sin^2 0{,}267°} \approx 46200 \quad C_{\max,2D} = \frac{A}{A'} = \frac{\sin 90°}{\sin 0{,}267°} \approx \sqrt{46200} = 215$$

Radiation concentration on parabolic mirrors

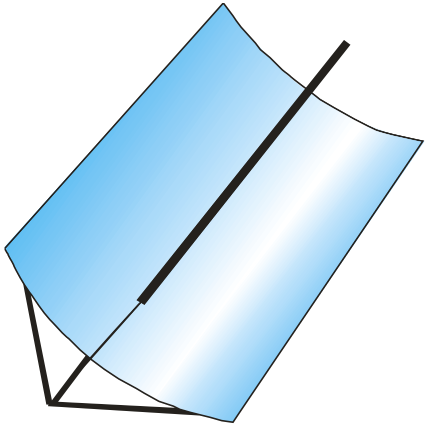
Parabolic mirrors have focal points



Point-focusing: paraboloid mirror

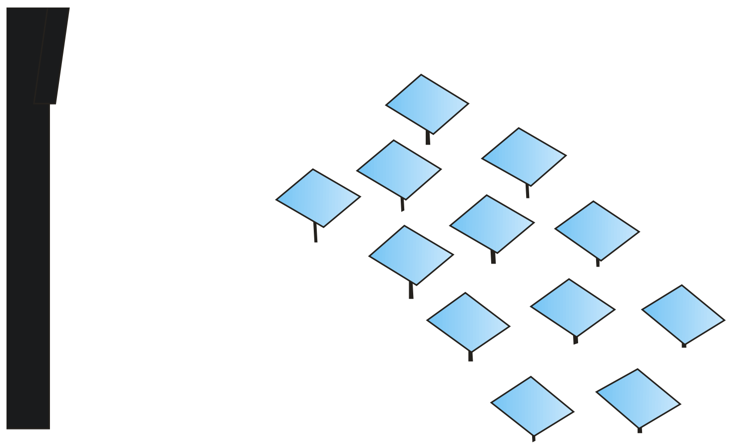


Line-focusing: parabolic troughs

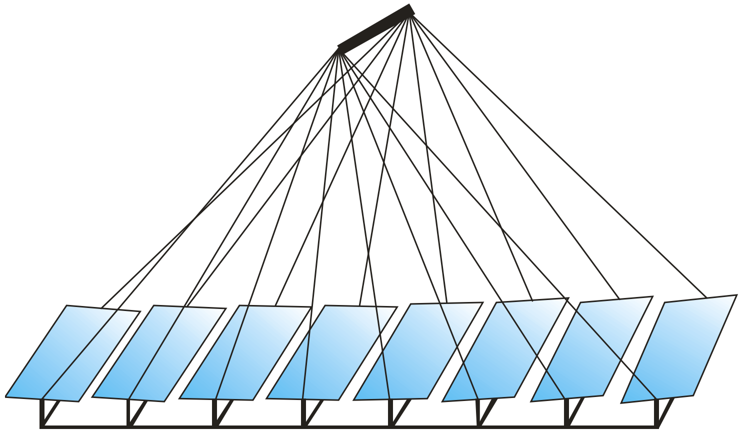


Alternative concentrating geometries

Point-focusing: heliostat field (solar tower plants)



Line-focusing: Fresnel mirror



Maximum mean concentration on paraboloid mirrors

$$C = \frac{A_{ap}}{A_{im}}$$

A_{ap} ... aperture area

A_{im} ... image area

$$A_{ap} = \pi r_r^2 \sin^2\psi$$

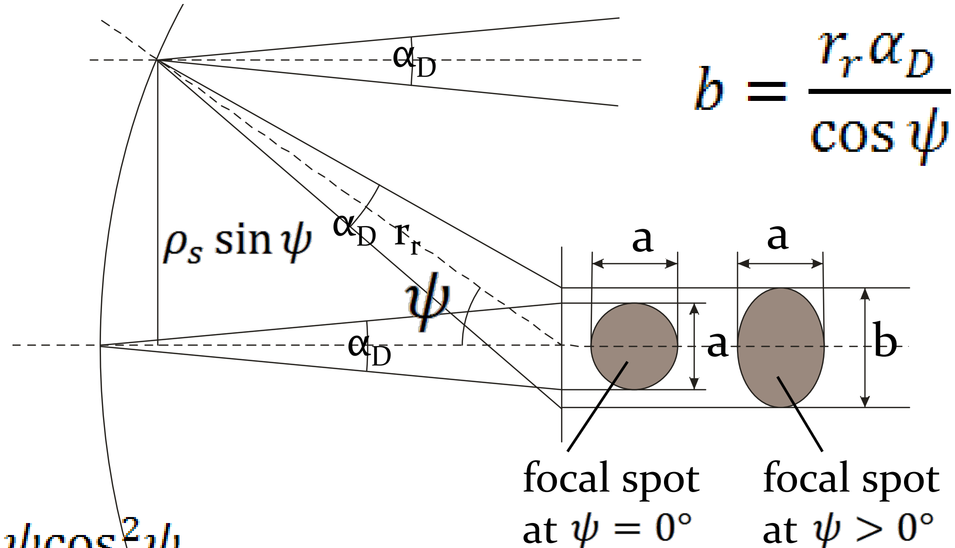
$$A_{im} = \frac{\pi}{4}\frac{r_r^2\alpha_D^2}{\cos^2\psi}$$

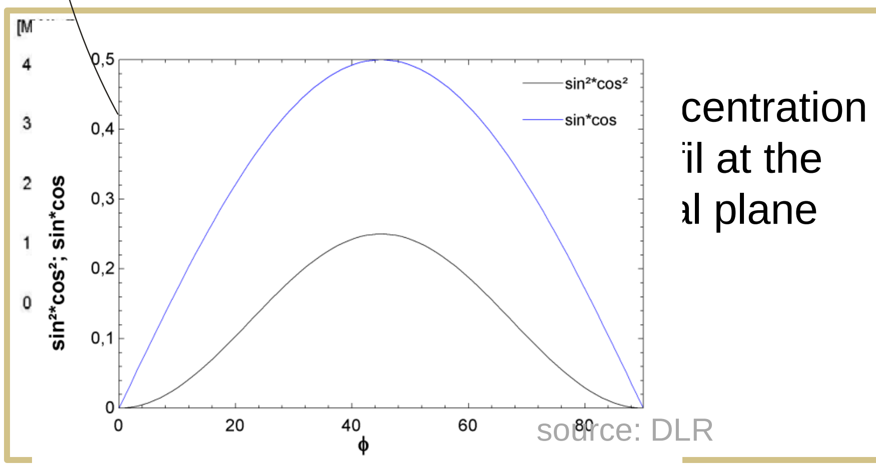
$$C = \frac{4}{\alpha_D^2}\sin^2\psi\cos^2\psi \;= 46200\sin^2\psi\cos^2\psi$$

$$C_{max} = 46200 \cdot 0.5 \cdot 0.5 = 11550$$

$$a = r_r\alpha_D$$

$$b = \frac{r_r\alpha_D}{\cos\psi}$$





source: DLR

Maximum mean concentration on parabolic troughs

$$C = \frac{A_{ap}}{A_{im}}$$

A_{ap} ... aperture area

A_{im} ... image area

$$A_{ap} = 2 l r_r \sin\psi$$

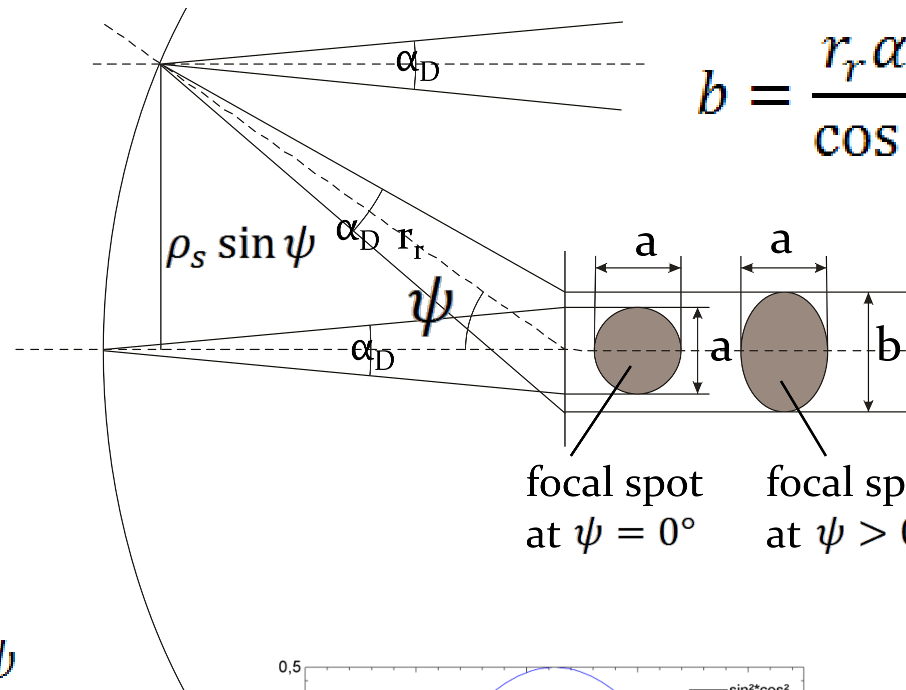
$$A_{im} = l \frac{r_r \alpha_D}{\cos\psi}$$

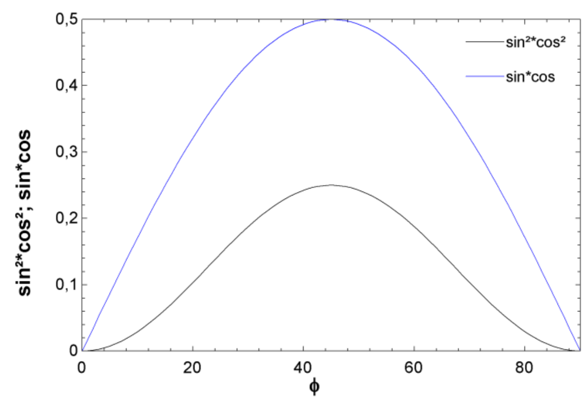
l ... trough length

$$C = \frac{2\sin\psi\cos\psi}{\alpha_D} = 215\sin\psi\cos\psi$$

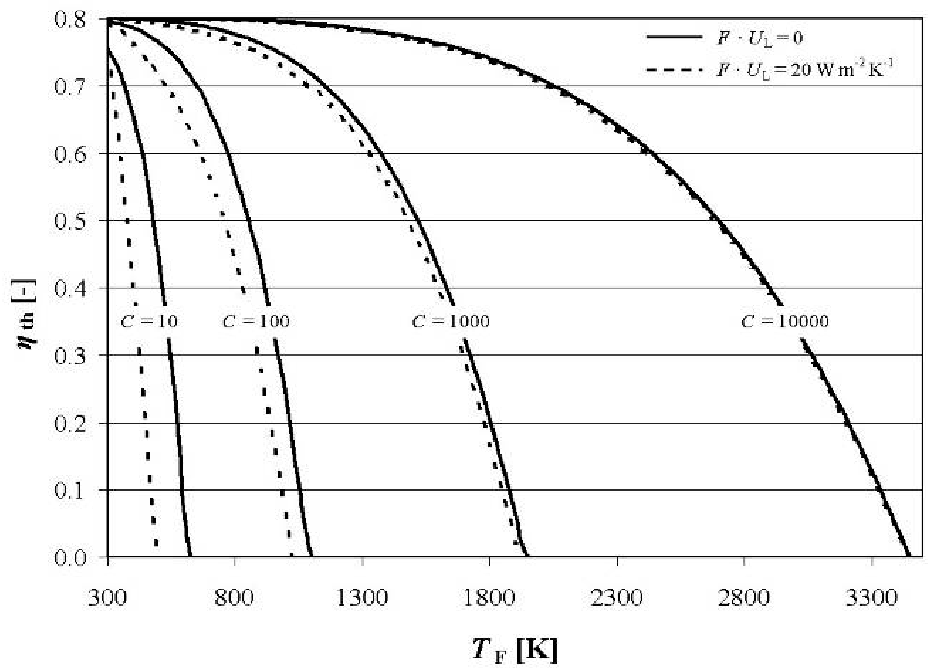
$$C_{max} = 215 \cdot \frac{1}{\sqrt{2}} \cdot \frac{1}{\sqrt{2}} = 107.5$$

$$b = \frac{r_r \alpha_D}{\cos\psi}$$





Maximum absorber temperature



$$T_{AB} = T_s\left(\frac{C}{C_{max}}\right)^{\frac{1}{4}} = 5780\text{K}\left(\frac{C}{46200}\right)^{\frac{1}{4}}$$

- selective coatings and claddings may increment the absorber temperature
- heat conduction and convection tend to reduce the absorber temperature
- atmospheric influences reduce the solar radiation and reduce the absorber temperature

highest possible absorber temperature (Second law of thermodynamics): 5780K

(= effective Sun temperature)

Carnot Cycle

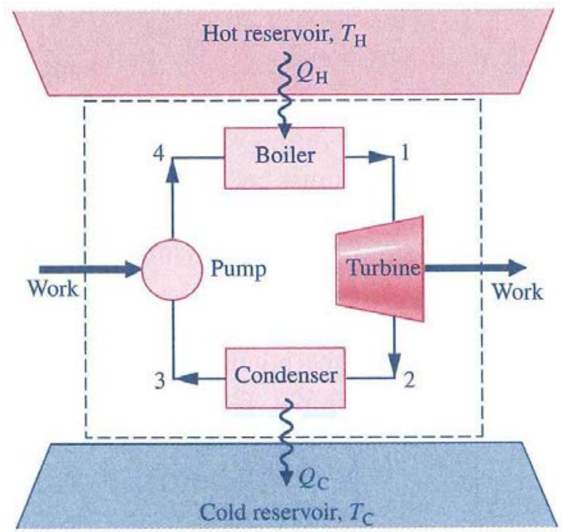
$$Q = \int T dS$$

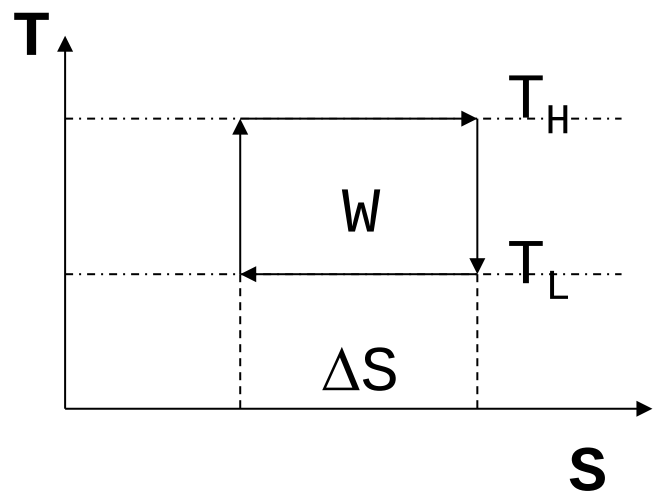
$$Q_{zu} = T_H \Delta S$$

$$Q_{ab} = T_L \Delta S$$

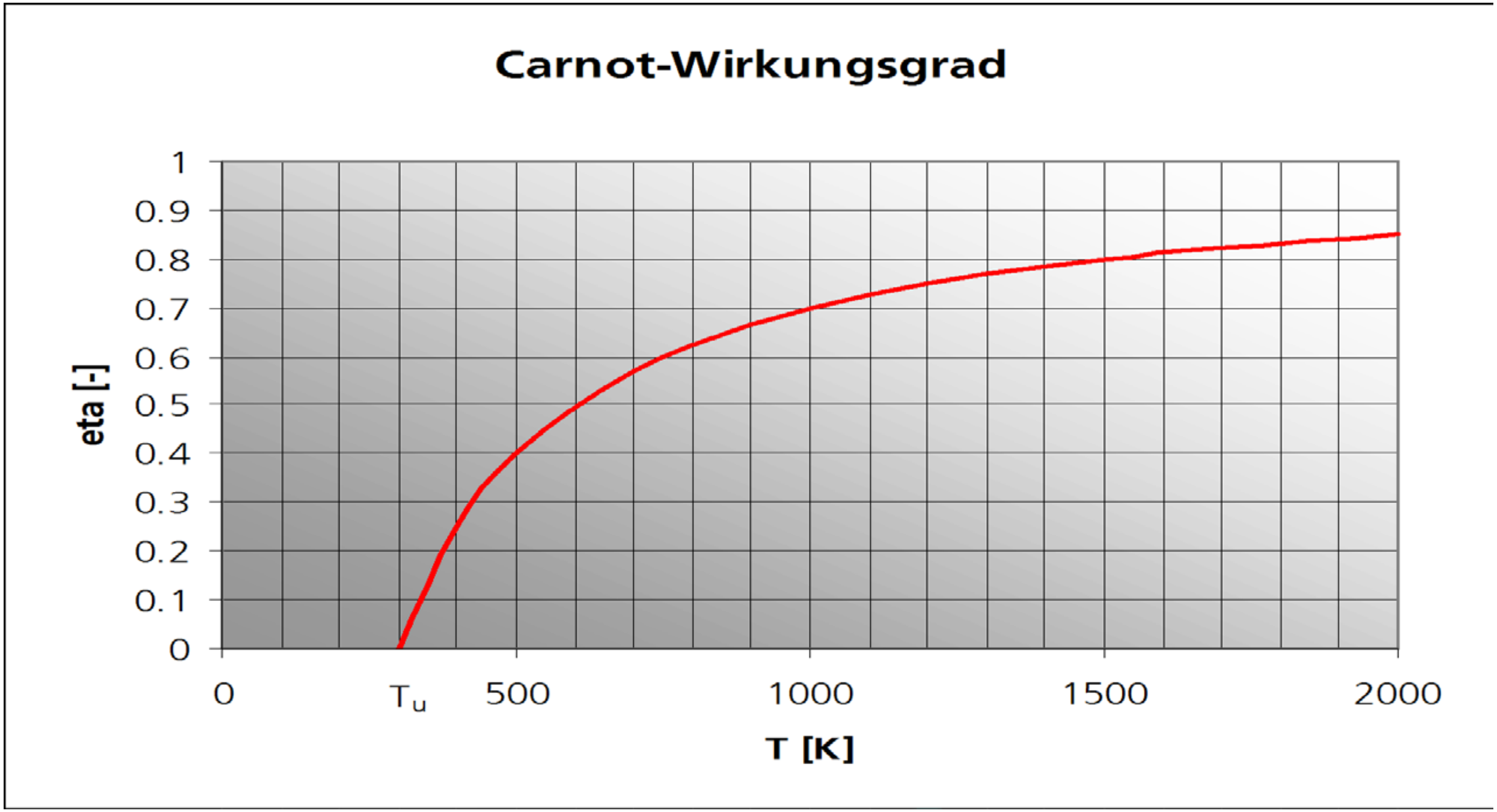
$$W = Q_{zu} - Q_{ab}$$

$$\eta = \frac{Q_{zu} - Q_{ab}}{Q_{zu}} = \frac{T_H - T_L}{T_H} = 1 - \frac{T_L}{T_H}$$



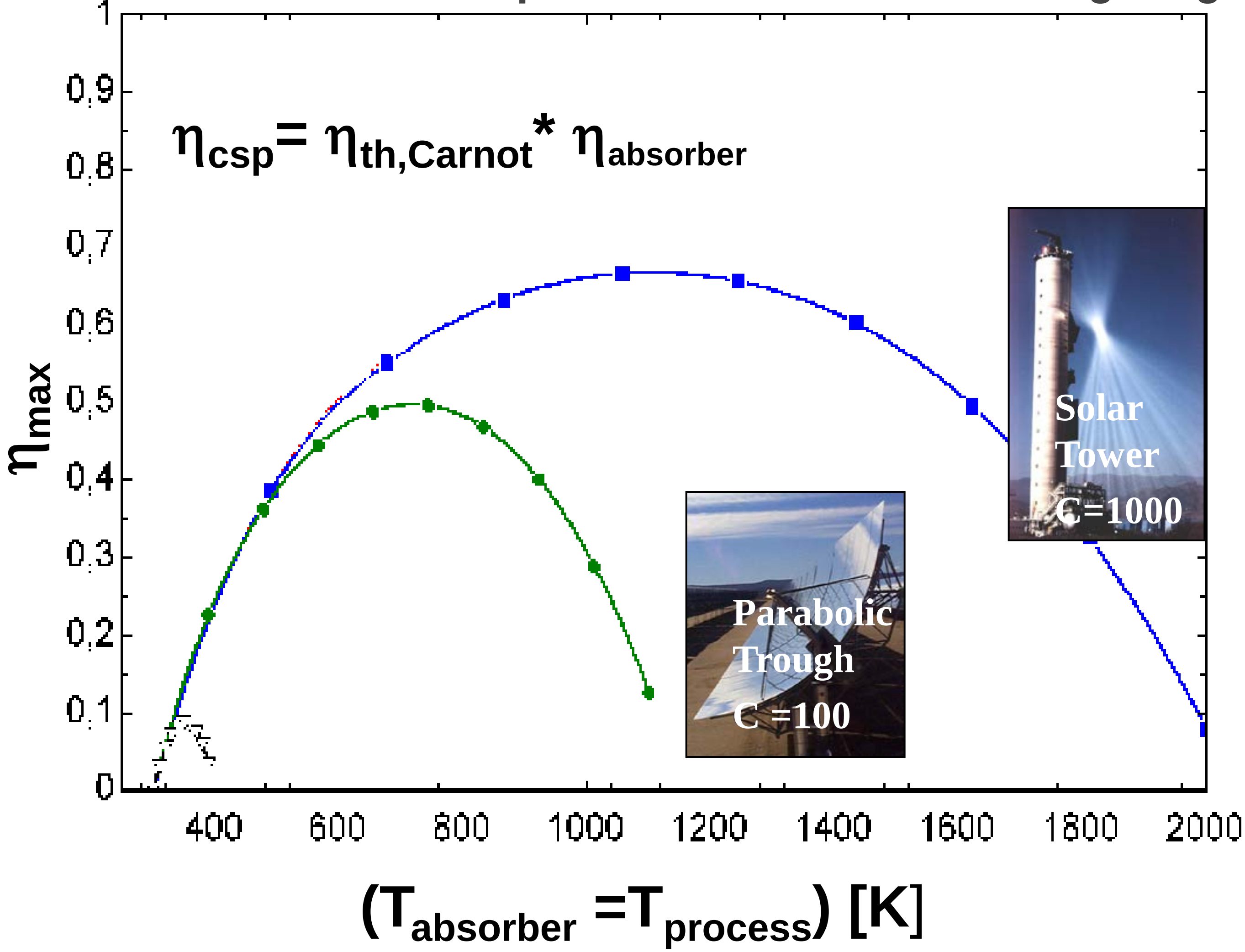


Effciency of a Carnot Cycle

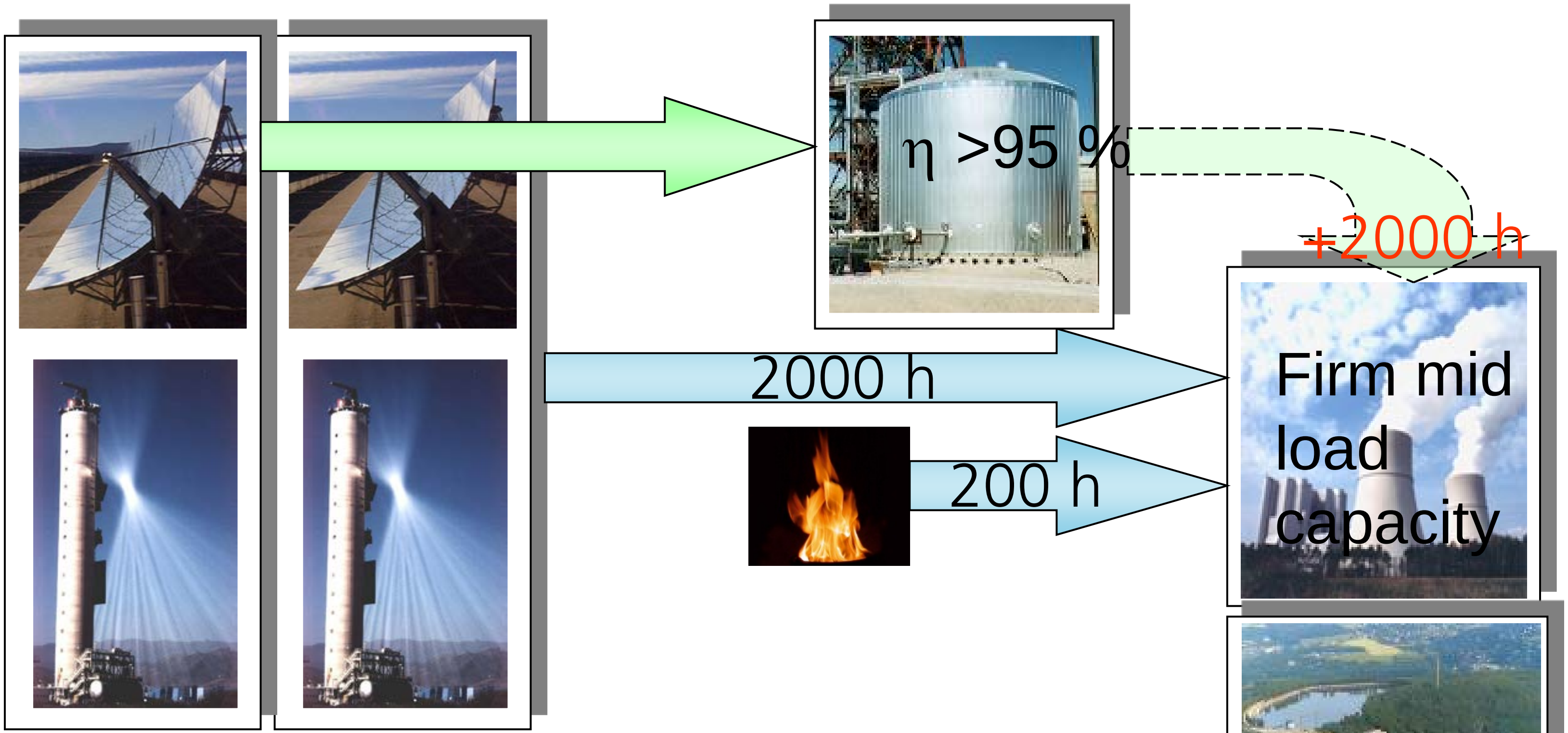


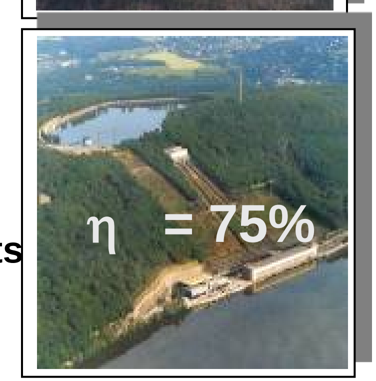
CSP F&E Strategie:

hohe Konzentration + hohe Temperatur = hohe Effizienz => geringe Kosten



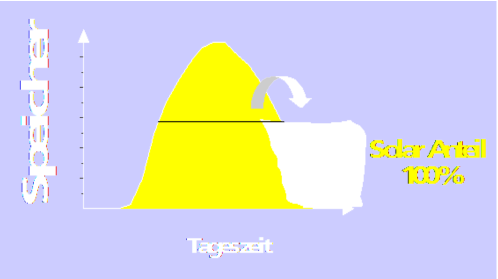
Thermal Storage vs. Electric Storage

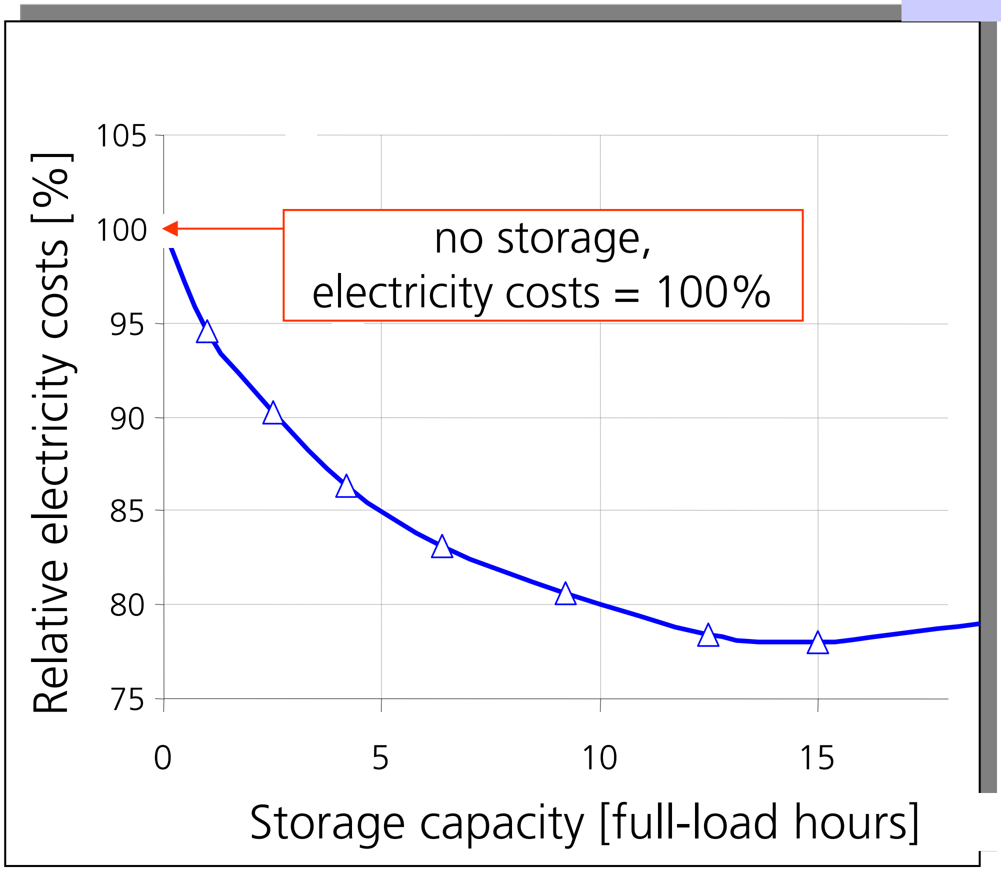




CSP with storage and fossil hybridisation can provide all 3 components
Thermal storage economically favorable

The Value of CSP Electricity

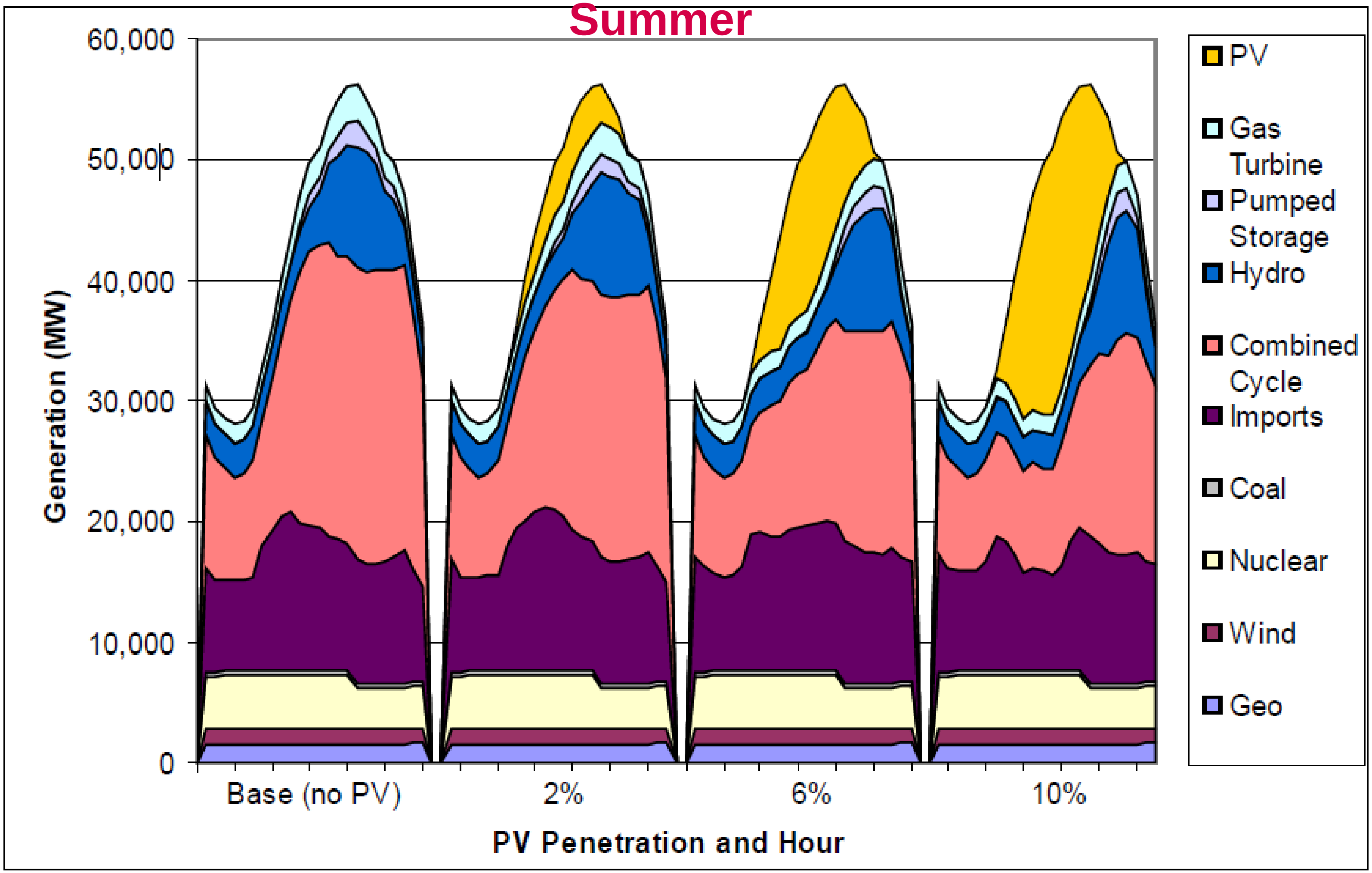




* assuming specific investment costs for the storage of 10 Euro/kWh

CSP vs PV

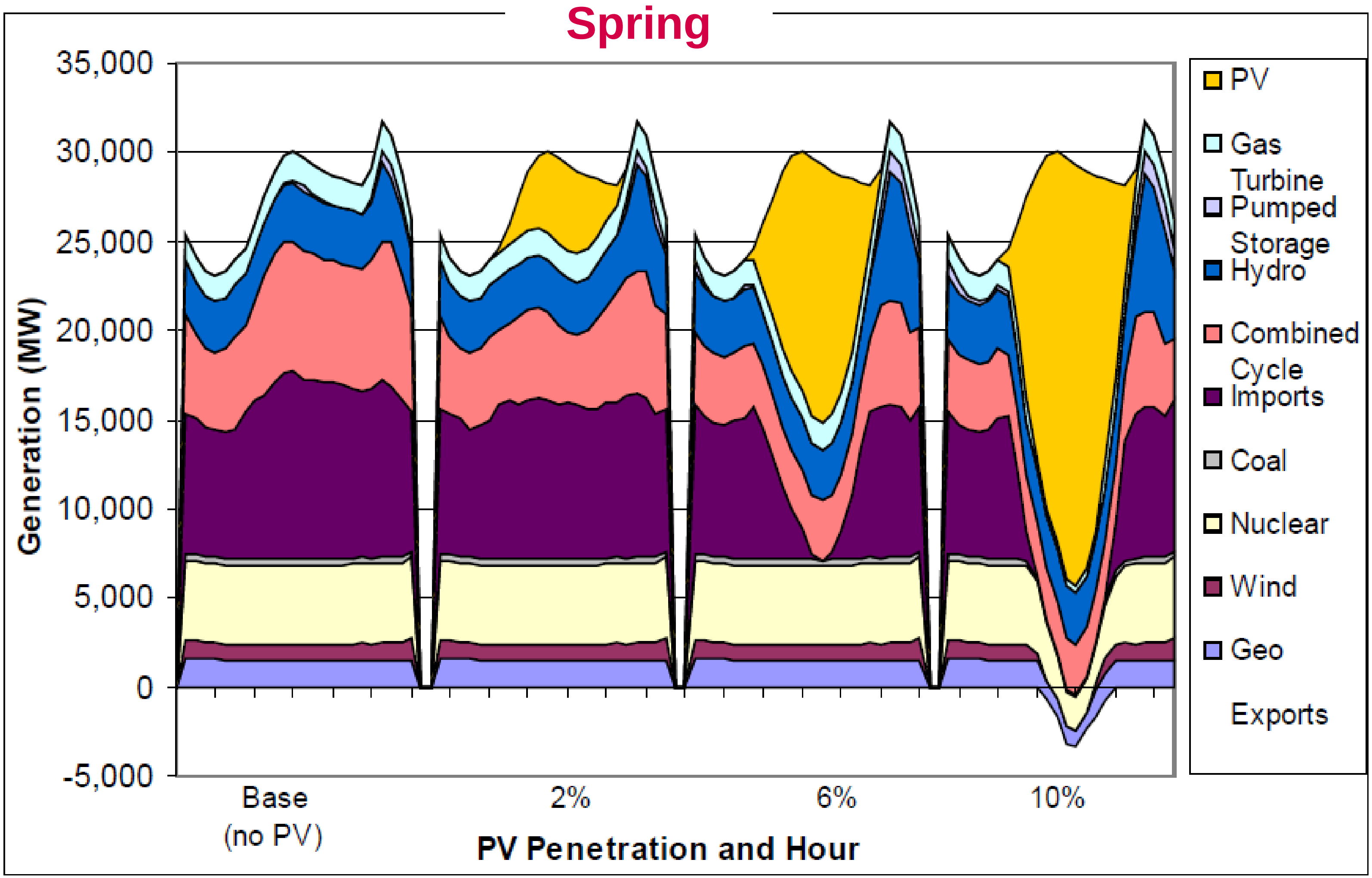
Simulation of supply and demand with increasing PV share



Source: NREL/TP-6A20-52978, Nov. 2011

CSP vs PV

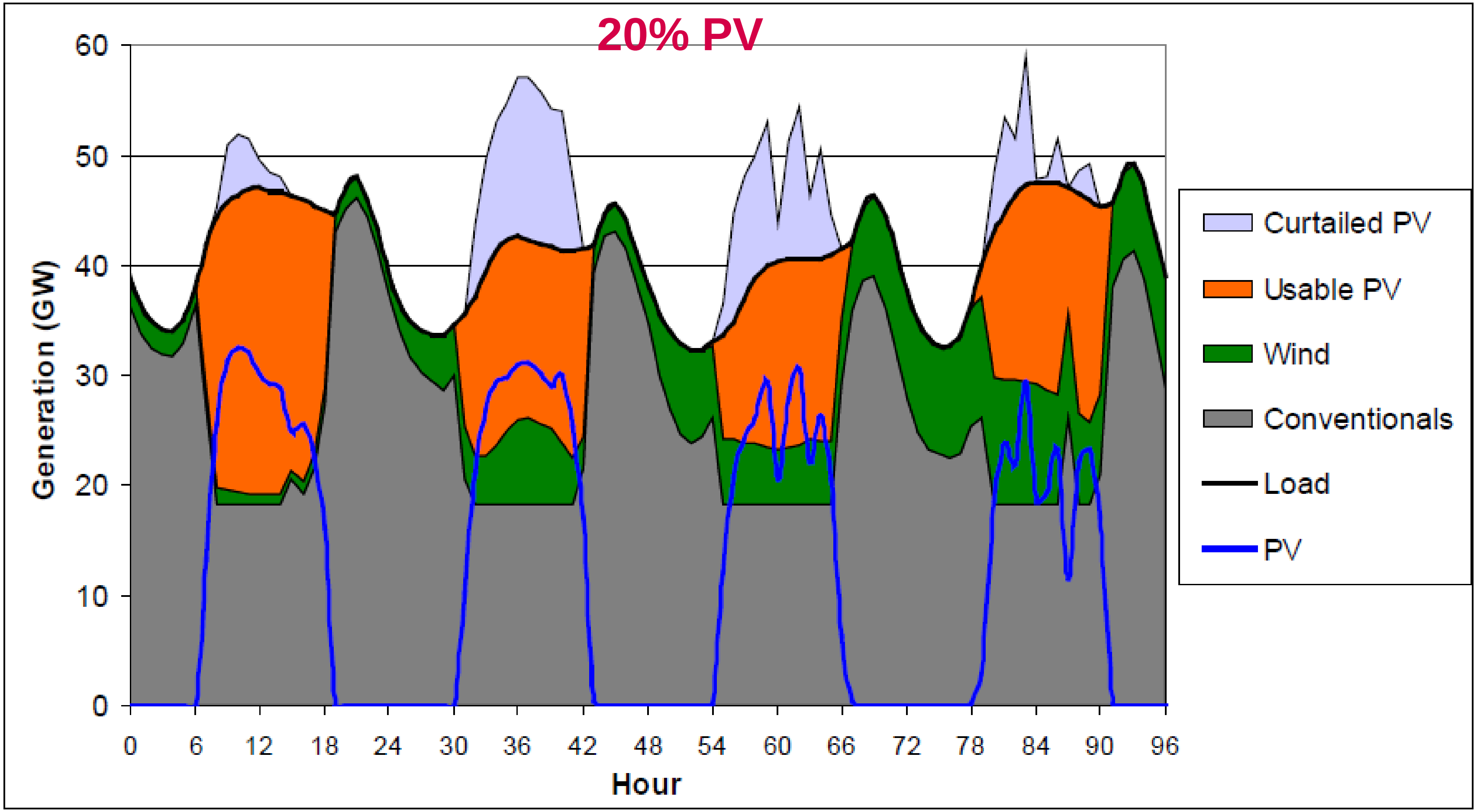
Simulation of supply and demand with increasing PV share



Source: NREL/TP-6A20-52978, Nov. 2011

CSP vs PV

Simulation of supply and demand with increasing PV share



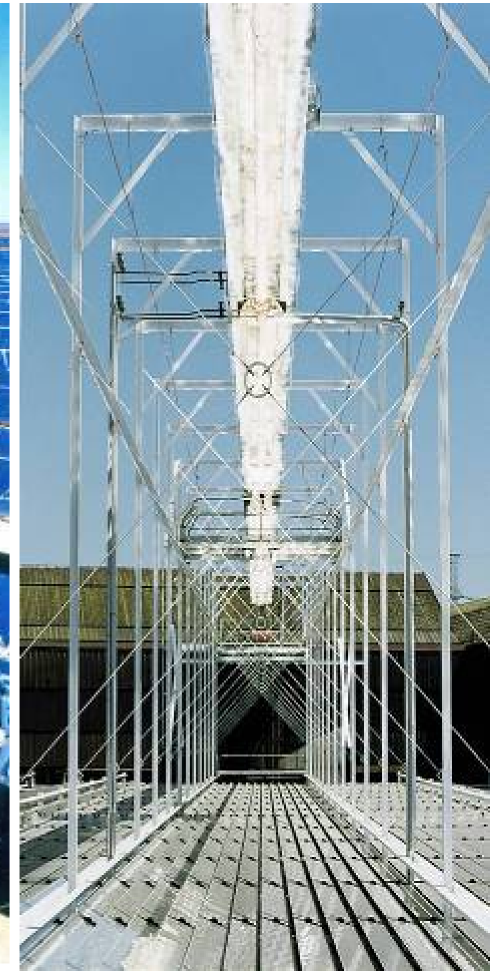
Source: NREL/TP-6A20-52978, Nov. 2011

Types of Concentrating Solar Thermal Technologies

Dish-Stirling

Solar Power Tower

Parabolic Trough

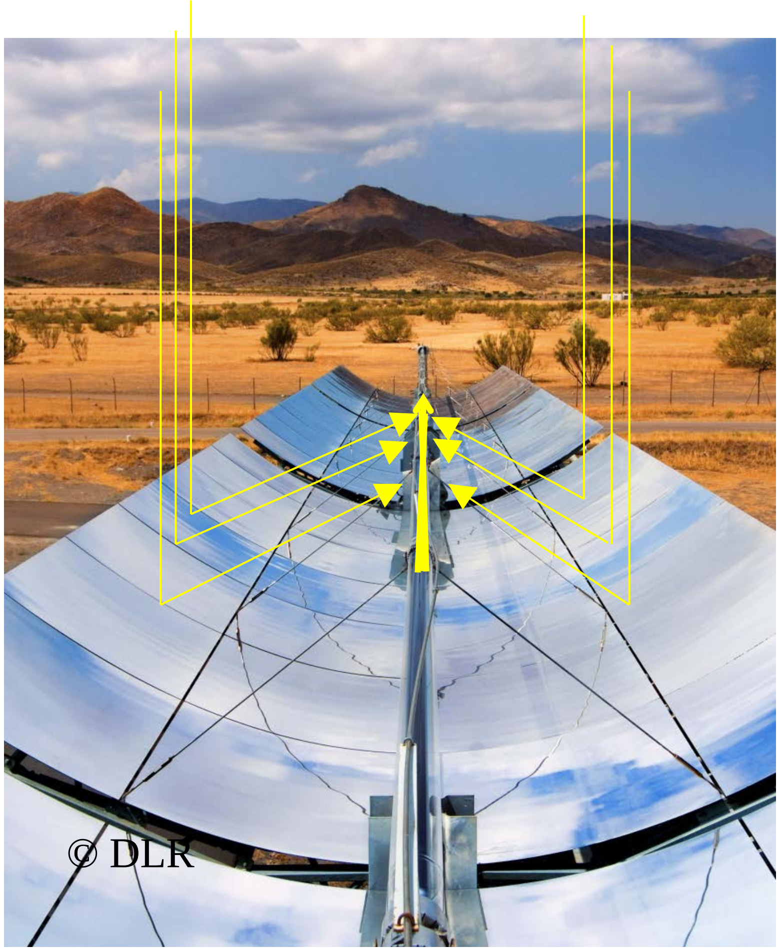


Linear Fresnel

DLR Deutsches Zentrum für Luft- und Raumfahrt e.V.
in der Helmholtz-Gemeinschaft

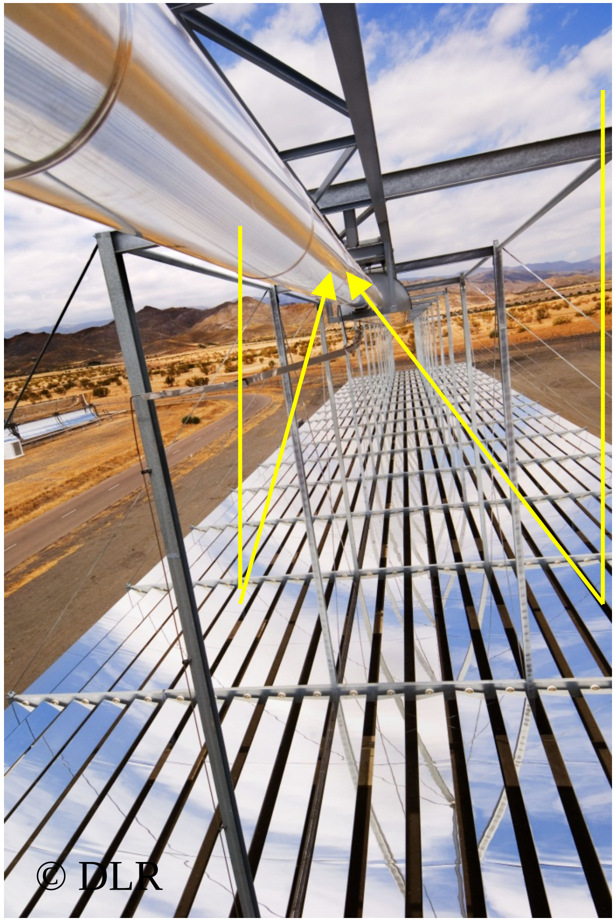
Parabolic Trough Collector

- Advantages:
  - Large scale proven technology
  - Bankable
- Disadvantages:
  - Up to now max. temperature of HTF limits the efficiency
  - Nearly flat side topography needed



Linear Fresnel Collector

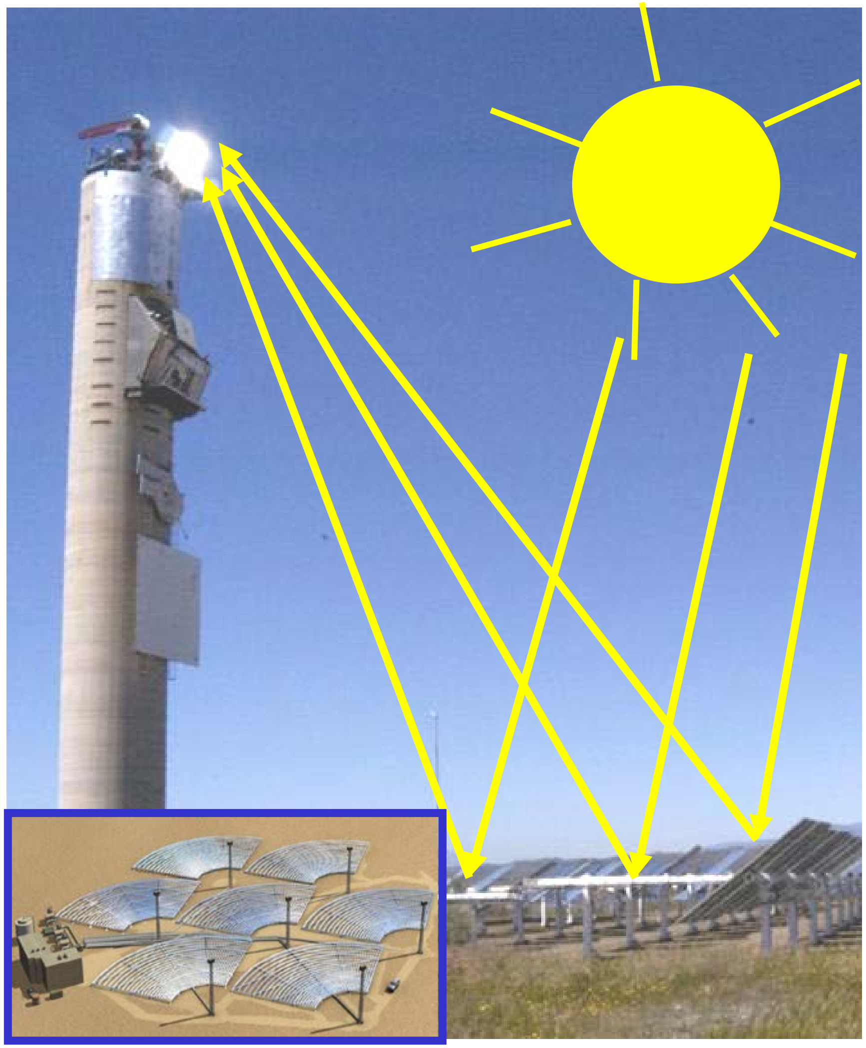
- Advantages:
  - Simple construction
  - High land use
  - Possible integration into buildings
- Disadvantages:
  - Low efficiency
  - State of the art without storage



Quelle: MSM

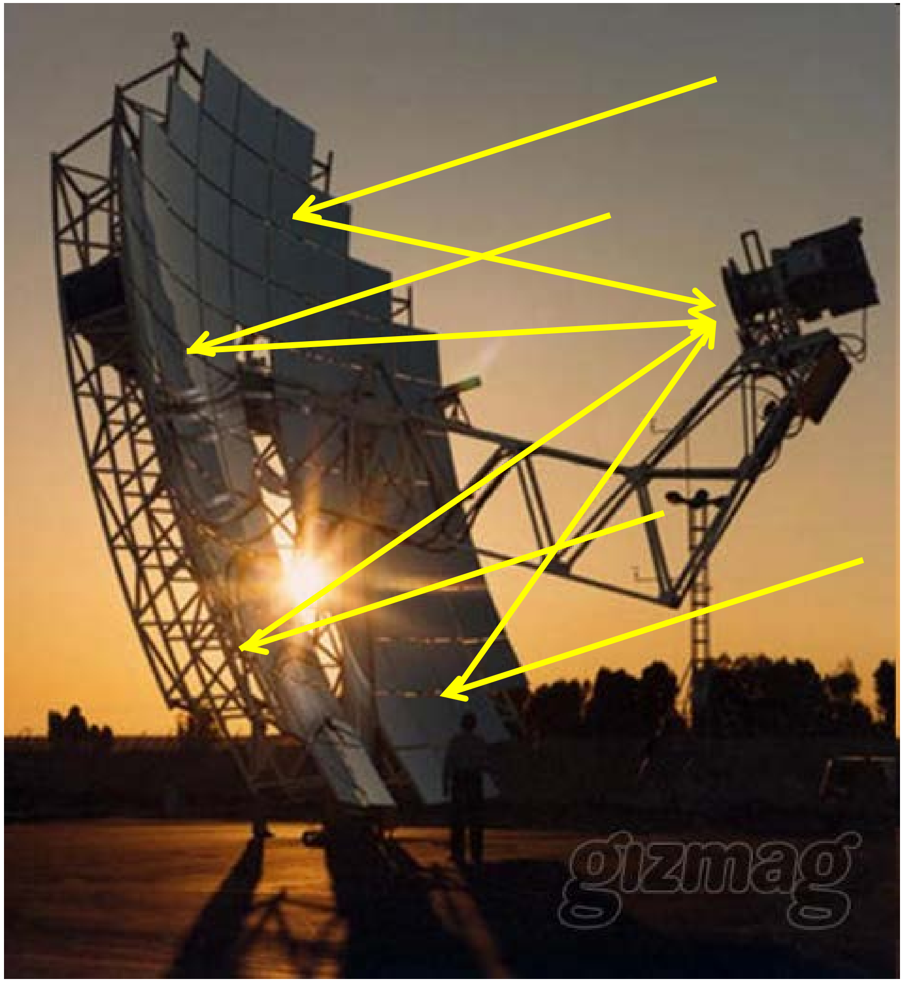
Solar Power Tower

- Advantages:
  - High efficiency potential
  - High cost reduction potential
  - Usable in hilly area
- Disadvantages:
  - Less commercial experience
  - Radiation attenuation by dust in the atmosphere



Dish-Stirling

- Advantages:
  - Very high efficiency
  - Small units
  - Decentralized application
- Disadvantages:
  - Expensive
  - No storage



Real data of CSP dispatchable generation (Andasol III data)

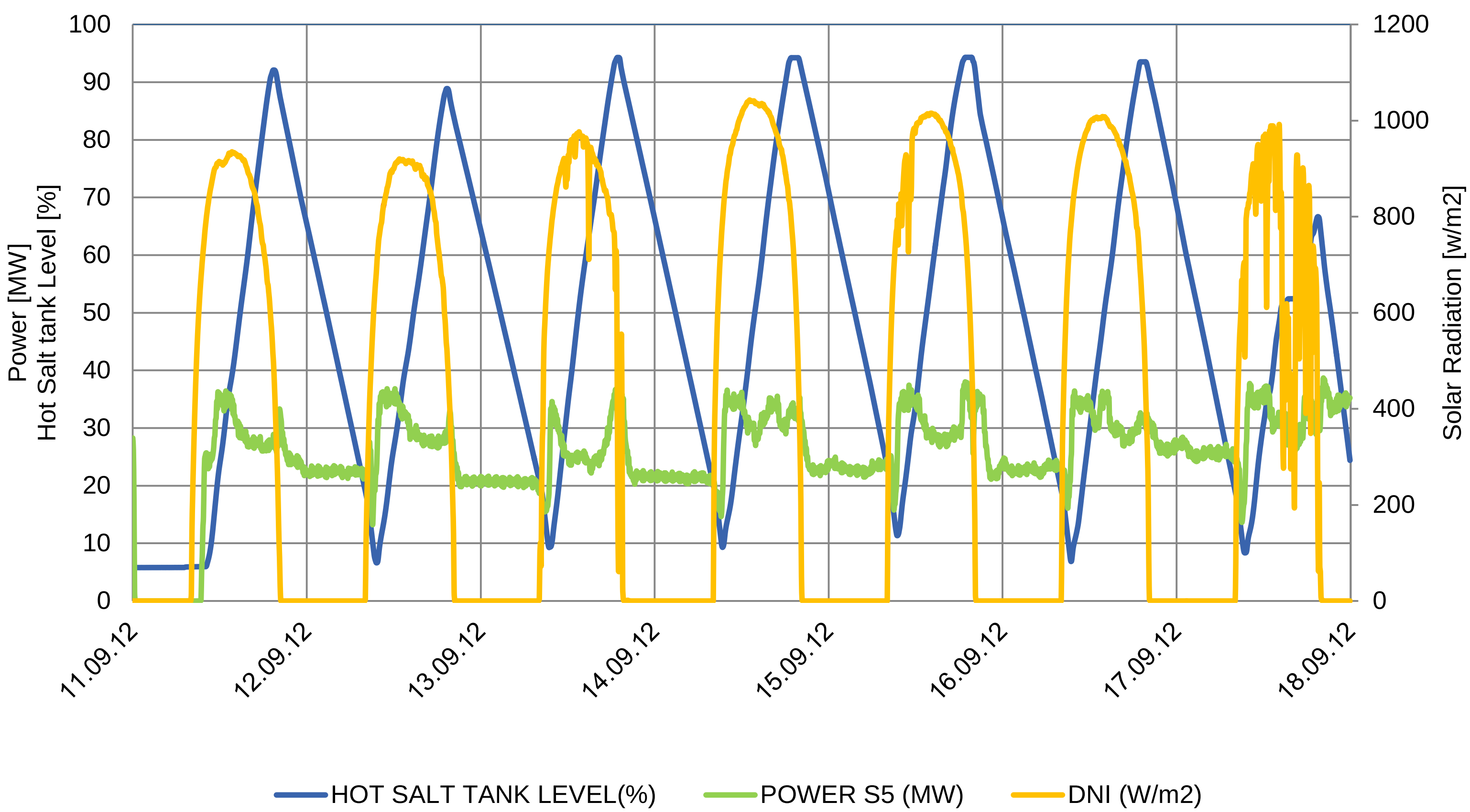
Andasol 3: Facts & Figures

- Owner: Marquesado Solar S.L.
- Location: Aldeire/La Calahorra (Granada, Spain)
- Technology: Parabolic trough incl. 7.5h molten salt storage
- Capacity: 50 MW_{el}
- Size of the collector area: ~ 500,000 m²
- Forecasted electricity production: ~200 GWh/a
- Annual CO_2 savings: 150,000 tonnes
- Commissioning in autumn 2011
- Investors: SWM Stadtwerke München, RWE The energy to lead, RheinEnergie, Solar Millennium, Ferrostaal
- EPC contractor: UTE Ferrostaal, duro felguera, s.a. energía, Solar Millennium, FLAGSOL

Source: RWE Innogy, F. Dinter

Continuous generation 24 h/d

11.09.2012 – 18.09.2012

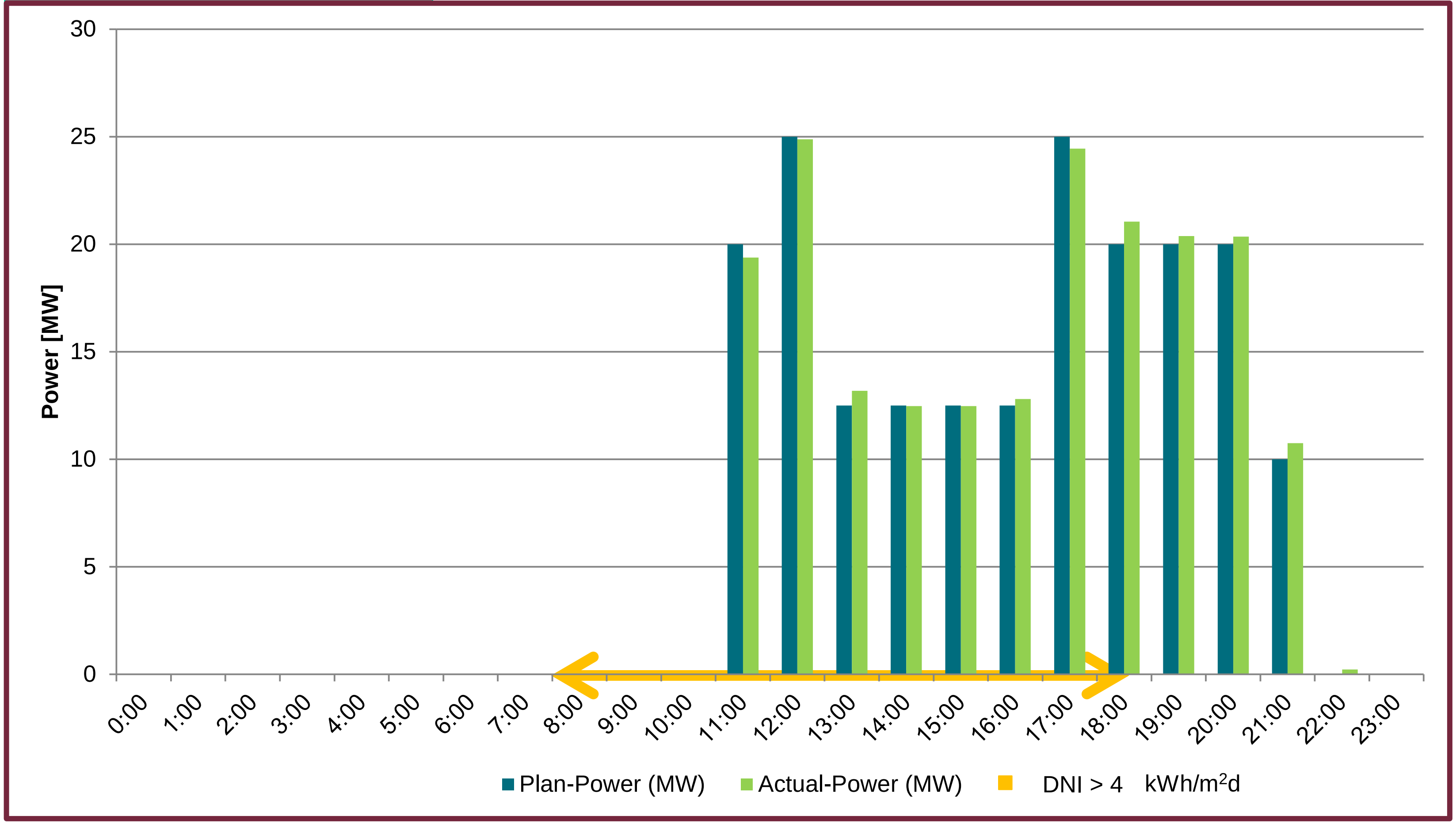


Source: RWE Innogy, F. Dinter

Dispatchable generation

Dispatchability test

22.03.2012

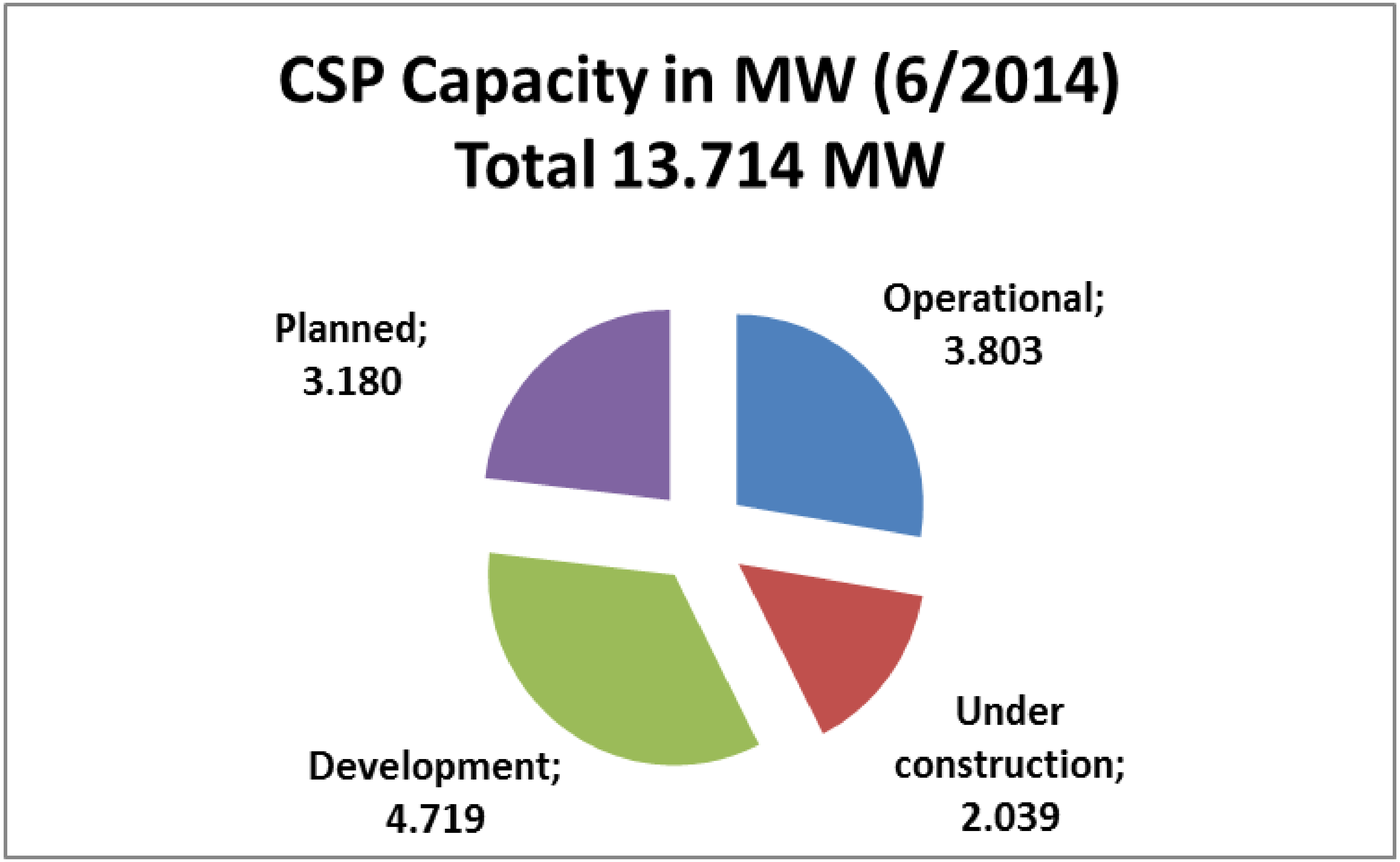


Source: RWE Innogy, F. Dinter

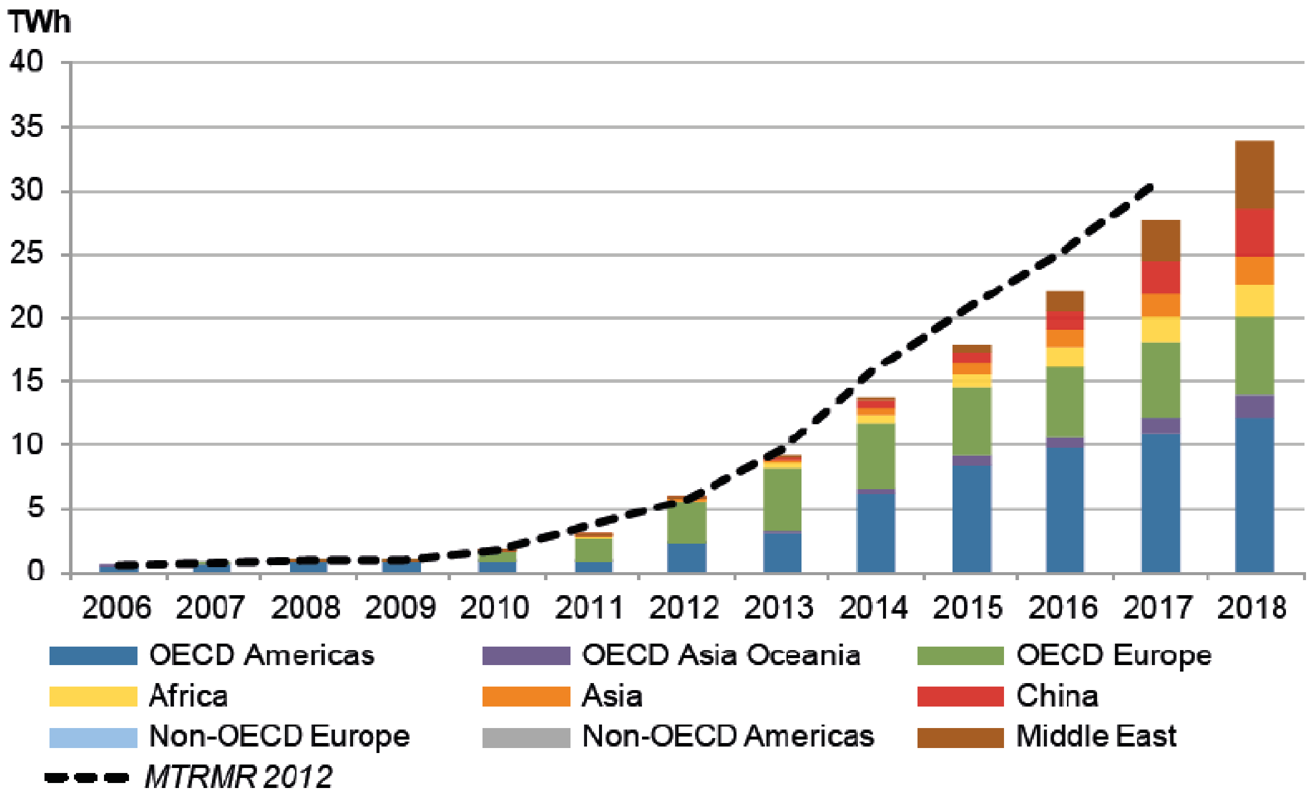
Market

Source: CSP Today Global Tracker www.csptoday.com/tracker

Market


CSP Capacity in MW (6/2014)
Total 13.714 MW
Operational; 3.803
Under construction; 2.039
Development; 4.719
Planned; 3.180

Market: Medium term generation to 2018

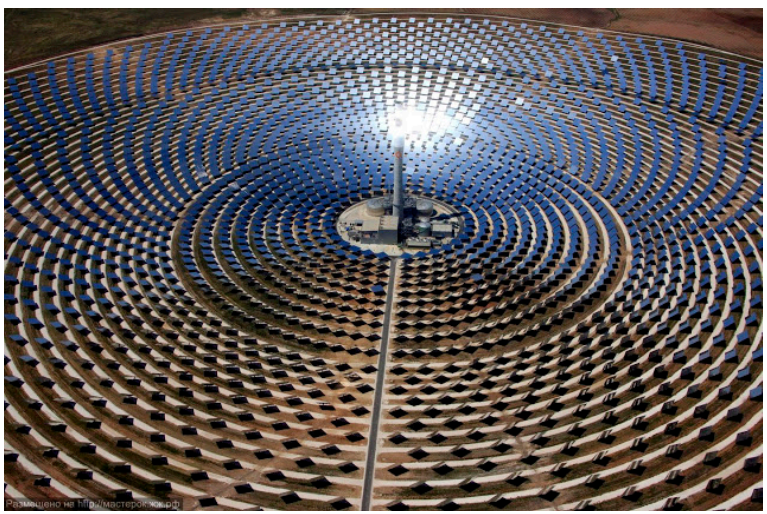


Ivanpah (Brightsource) solar tower 130 MW connected to grid, S eptember 24, 2013 (Total 390 MW)

Technology:	Power tower
Status:	Operational
Country:	United States
City:	Primm, NV
State:	California
County:	San Bernardino
Lat/Long Location:	35°33′ 8.5″ North, 115°27′ 30.97″ West
Land Area:	3,500 acres
Solar Resource:	2,717 $kWh/m^2/yr$
Source of Solar Resource:	NREL Solar Power Prospector
Electricity Generation:	1,079,232 MWh/yr (Expected/Planned)
Contact(s):	Andy Taylor
Company:	BrightSource Energy
Key References:	Web site
Break Ground:	October 2010
Start Production:	February 13, 2013
Cost (approx):	2,200 USD million
Construction Job-Years:	1896
Annual O&M Jobs:	90
PPA/Tariff Date:	January 2010
PPA/Tariff Period:	25 years
Project Type:	Commercial
Incentives:	$1.6 billion in federal loan guarantees

Cresent Dunes

(100 MW Molten Salt, 6 h Storage)



Crescent Dunes Solar Energy Project

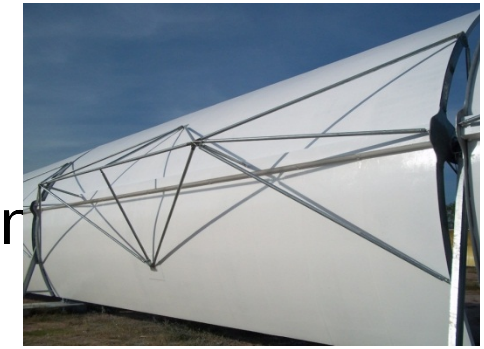
This page provides information on Crescent Dunes Solar Energy Project, a concentrating solar power (CSP) project, with data organized by backgrounc participants, and power plant configuration.

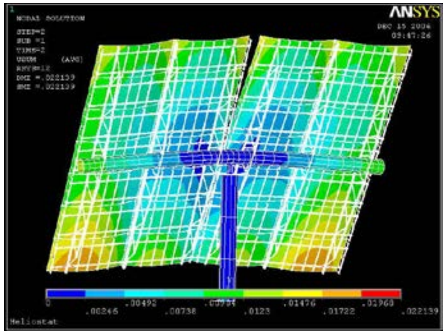
Status Date: February 26, 2013

Background

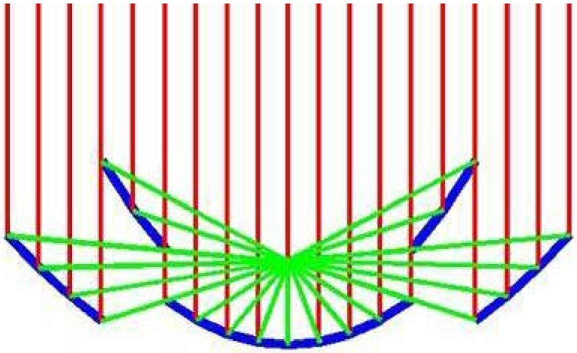
Technology:	Power tower
Status:	Under construction
Country:	United States
City:	Tonopah
State:	Nevada
County:	Nye
Region:	Northern Nevada, northwest of Tonopah
Lat/Long Location:	38°14′ North, 117°22′ West
Land Area:	1,600 acres
Solar Resource:	2,685 kWh/m^2/yr
Source of Solar Resource:	NREL Solar Power Prospector
Electricity Generation:	485,000 MWh/yr (Expected)
Contact(s):	Tom Georgis; Rob Howe
Company:	SolarReserve
Key References:	Press release Press release
Break Ground:	April 2011
Start Production:	October 2013
Construction Job-Years:	1500
Annual O&M Jobs:	200
PPA/Tariff Date:	December 22, 2009
PPA/Tariff Rate:	0.135 US$ per kWh
PPA/Tariff Period:	25 years
Project Type:	Commercial

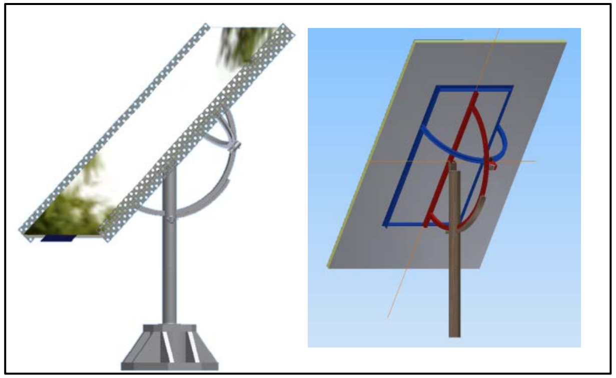
Challenges: Collectors





- Lightweight construction



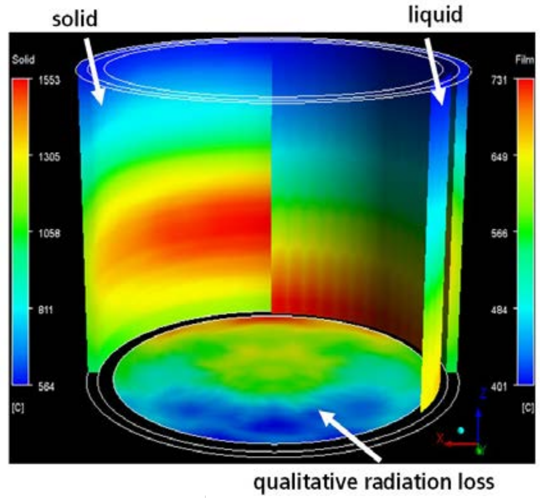


- New designs

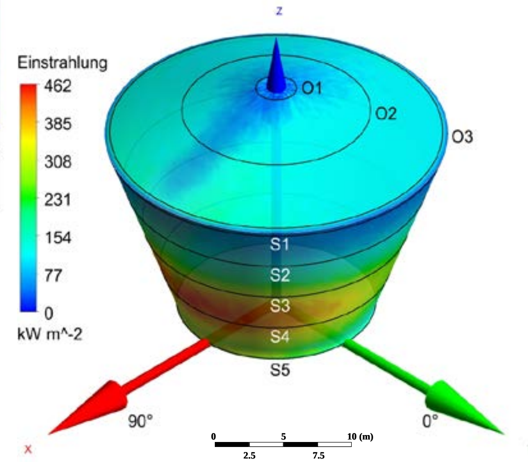
- Entire collector performance measurement
- and STANDARDs

Challenges: Heat Transfer Fluids for Higher Temperature

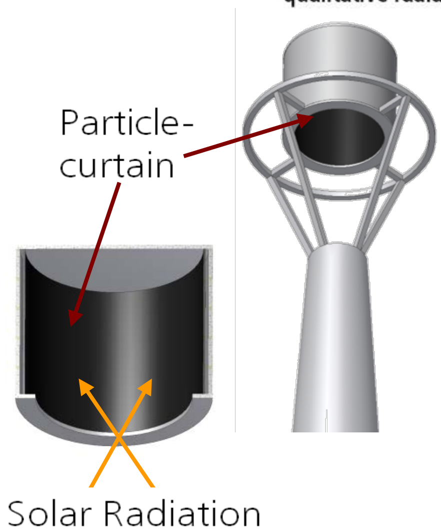
- Liquid salt



- Liquid metal

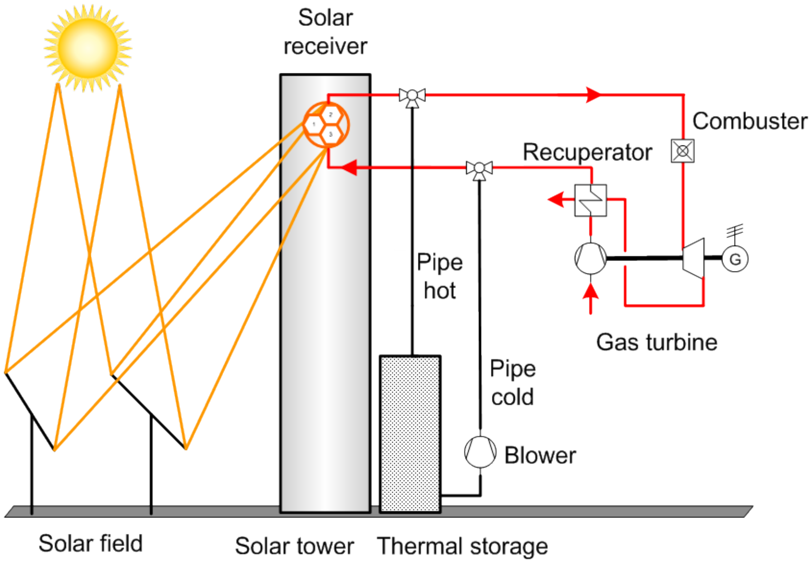


- Particles

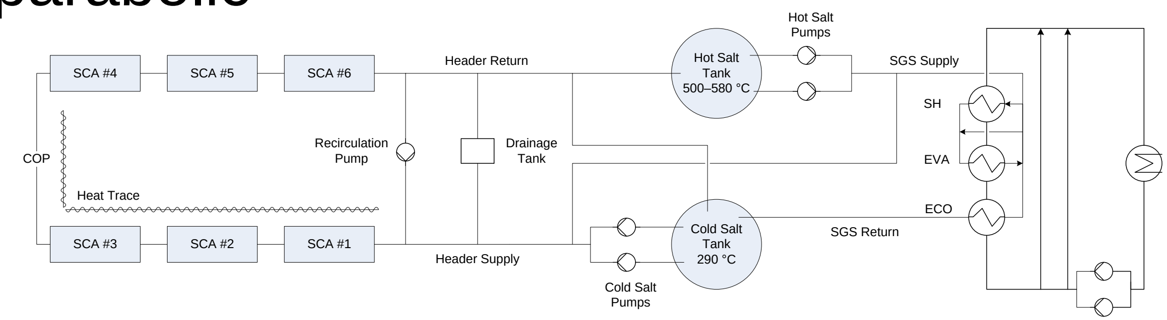


Challenges: Advanced Solar Power Cycles (Solarized Design)

- Top-cycles with pressurized air, liquid salt, liquid metal or particles



- Molten salt in parabolic troughs



Conclusion

- CSP is **one of the possible CO2 free systems** for electricity production
- CSP systems can be **equipped with a high efficient storage** system, enabling them **to deliver dispatchable electric** power
- CSP enables a **higher feeding of PV and wind** power to the grid
- The demand for cost reduction of CSP systems lead to
  - **Higher temperatures** of the heat transfer fluid
  - **Higher steam parameters**
  - **New heat transfer fluids** like molten salt, liquid metal and particle


Thank you for your attention