

# Solar Energy 2

Concentrating Solar Power

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**Chair Solar Technology  
Aachen University**



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



# What ist CSP?

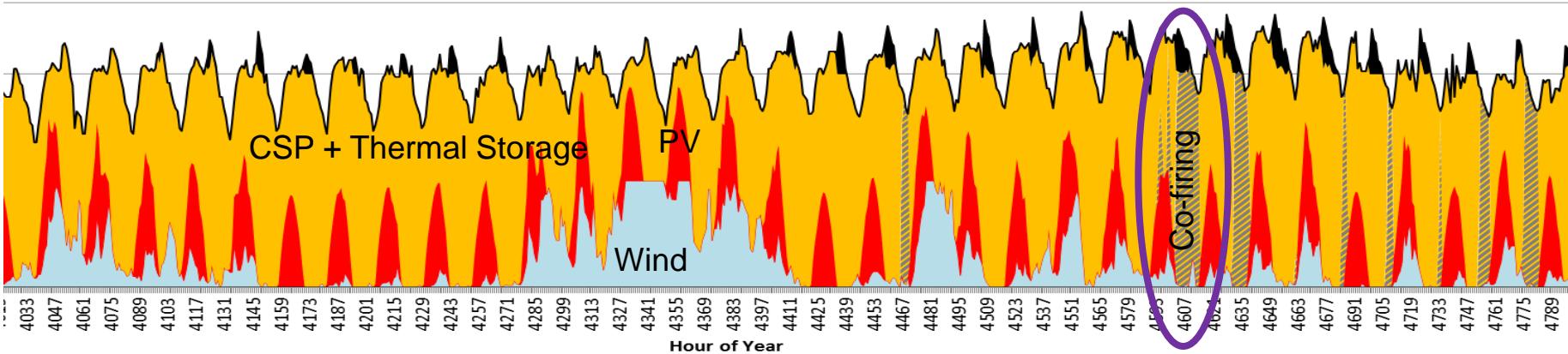
Heat

Thermal Storage

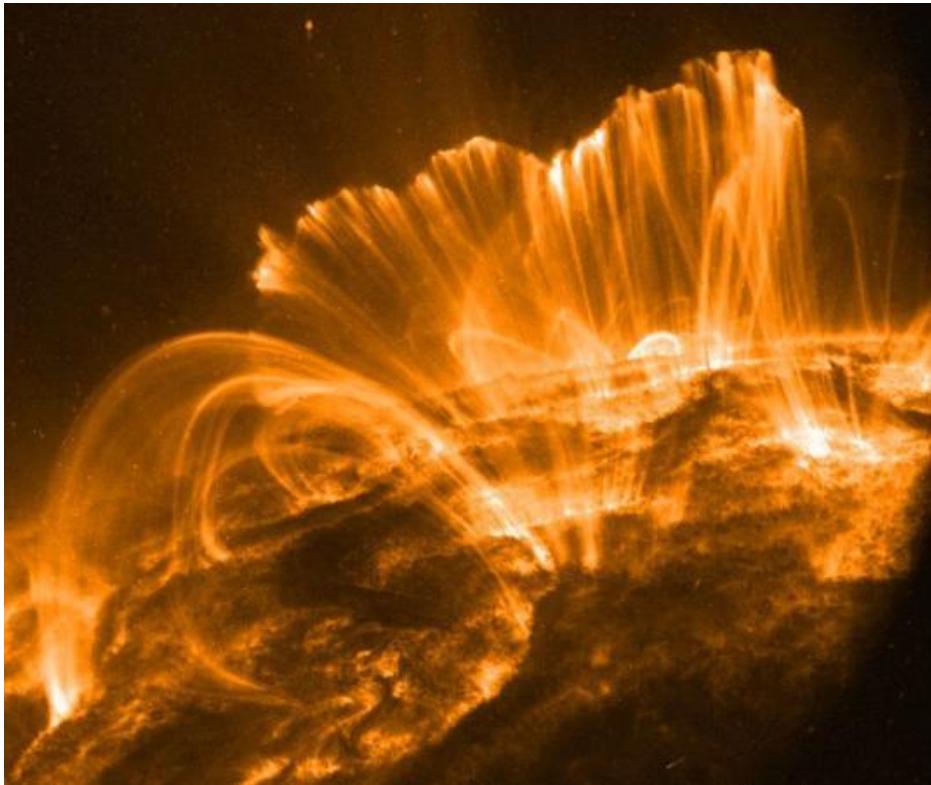
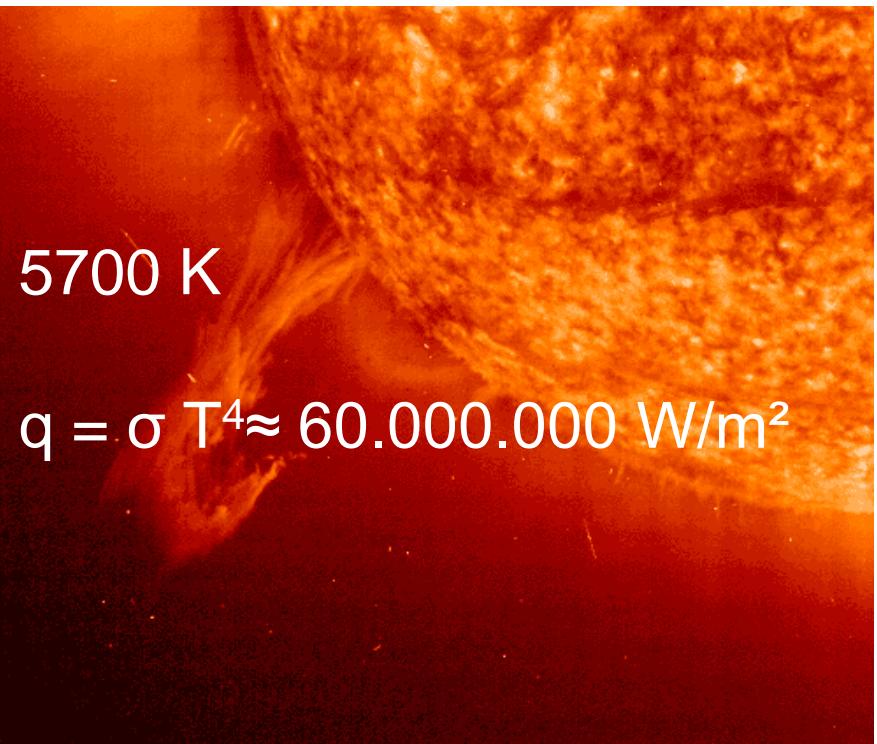
Heat

Turbine

Electricity

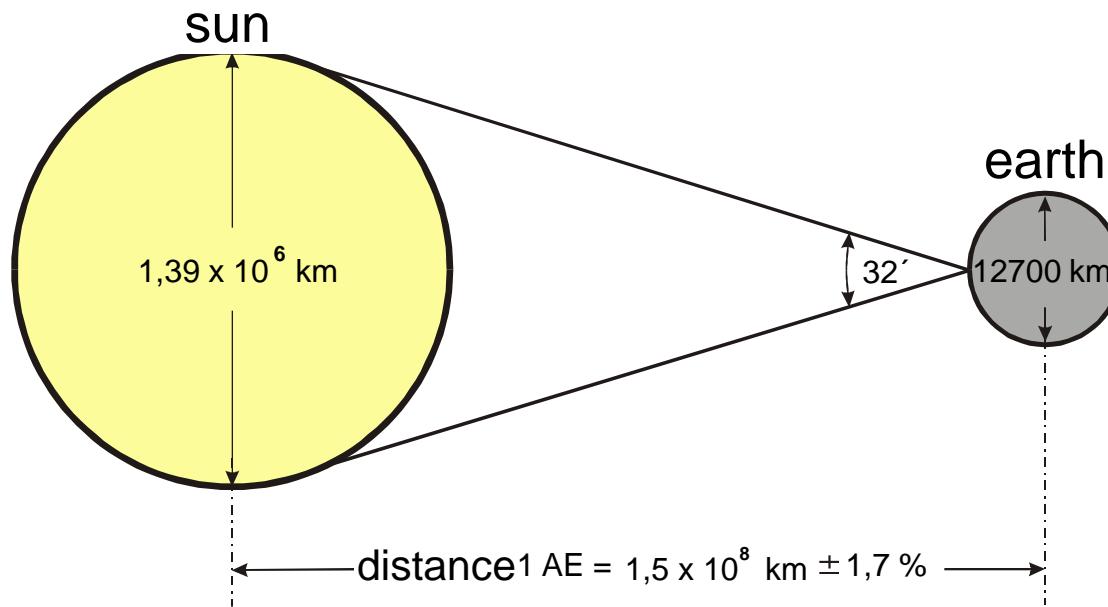


# Pictures of the sun surface



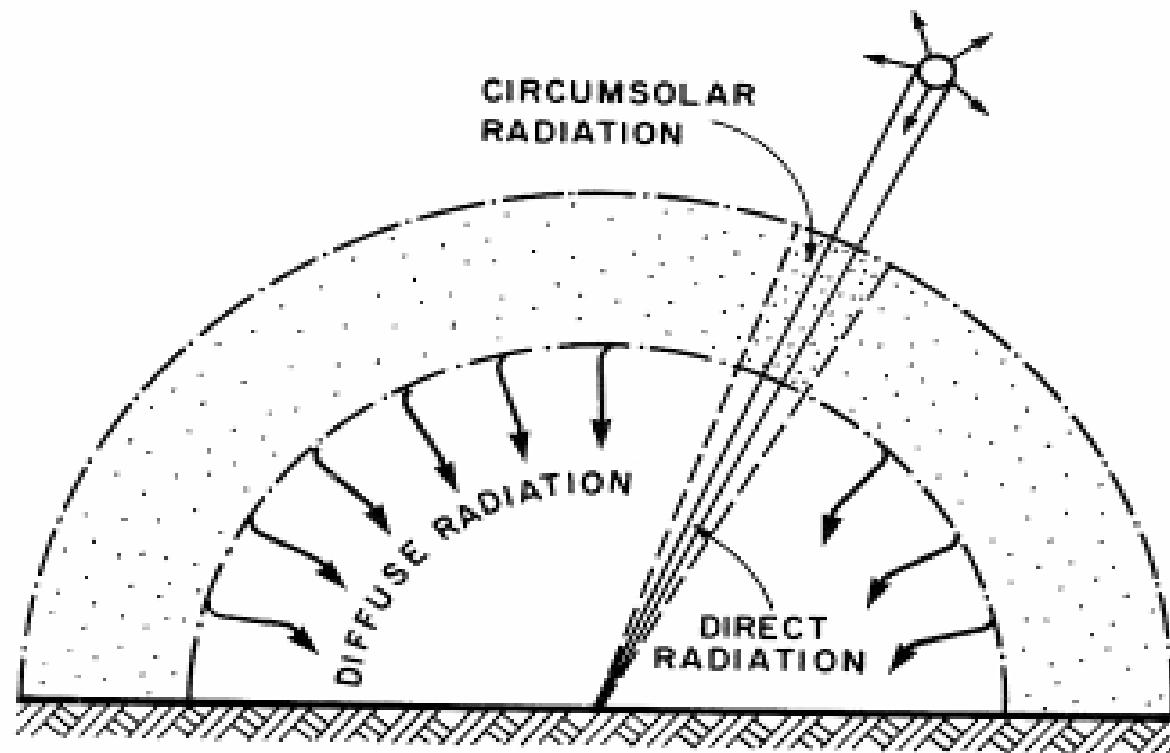
# Solar constant $I_0$

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



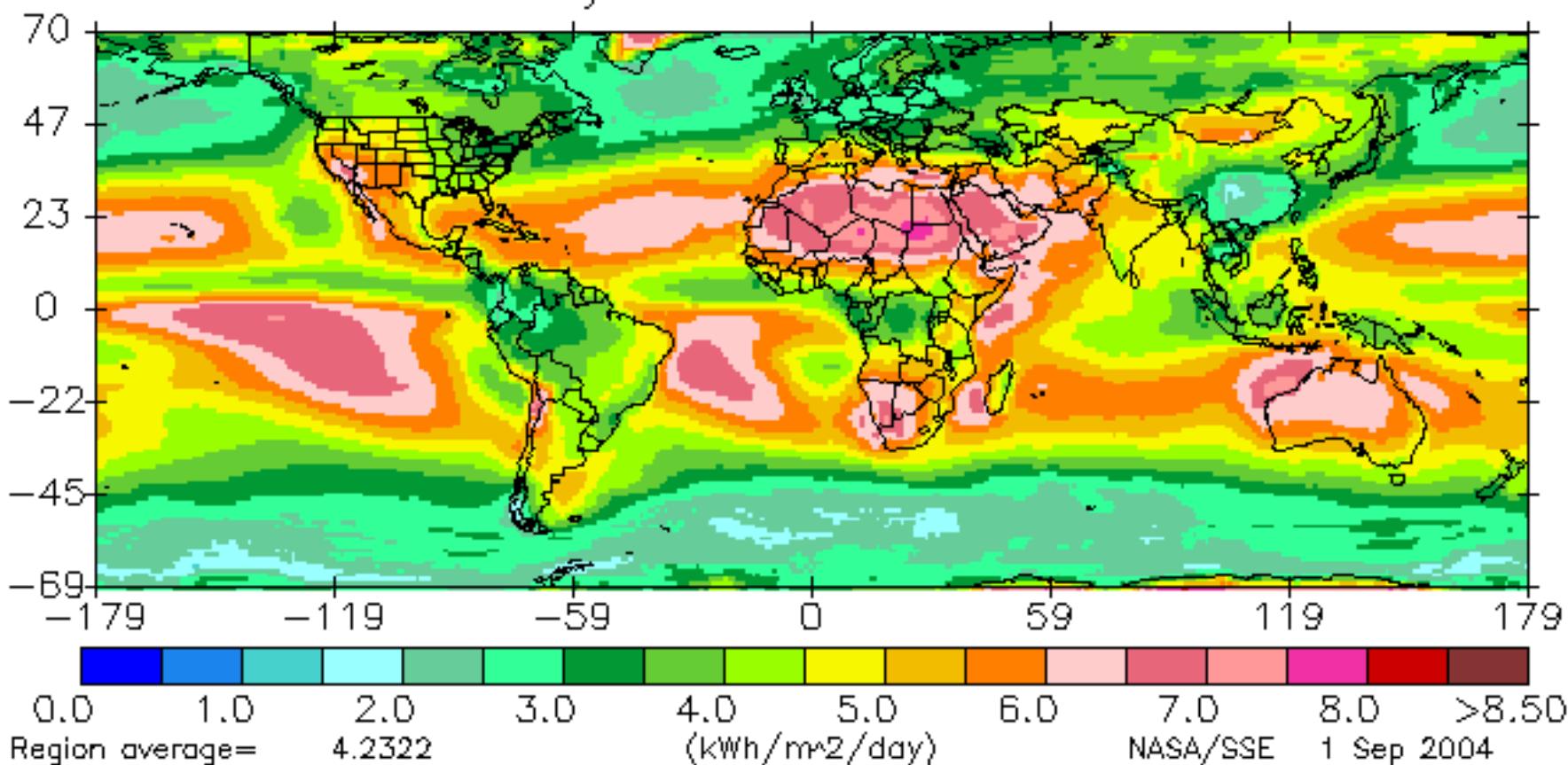
$$\frac{I_0}{I_s} = \frac{A_s}{A_{AE}} = \frac{4 \cdot \pi \cdot R_s^2}{4 \cdot \pi \cdot AE^2}, \quad I_0 = I_s \cdot \frac{R_s^2}{AE^2} = \sigma \cdot T_s^4 \cdot \frac{R_s^2}{AE^2} \approx 1360 \text{ W/m}^2 = 4870 \text{ kJ/(m}^2 \text{ y})$$

# Diffuse and direct radiation

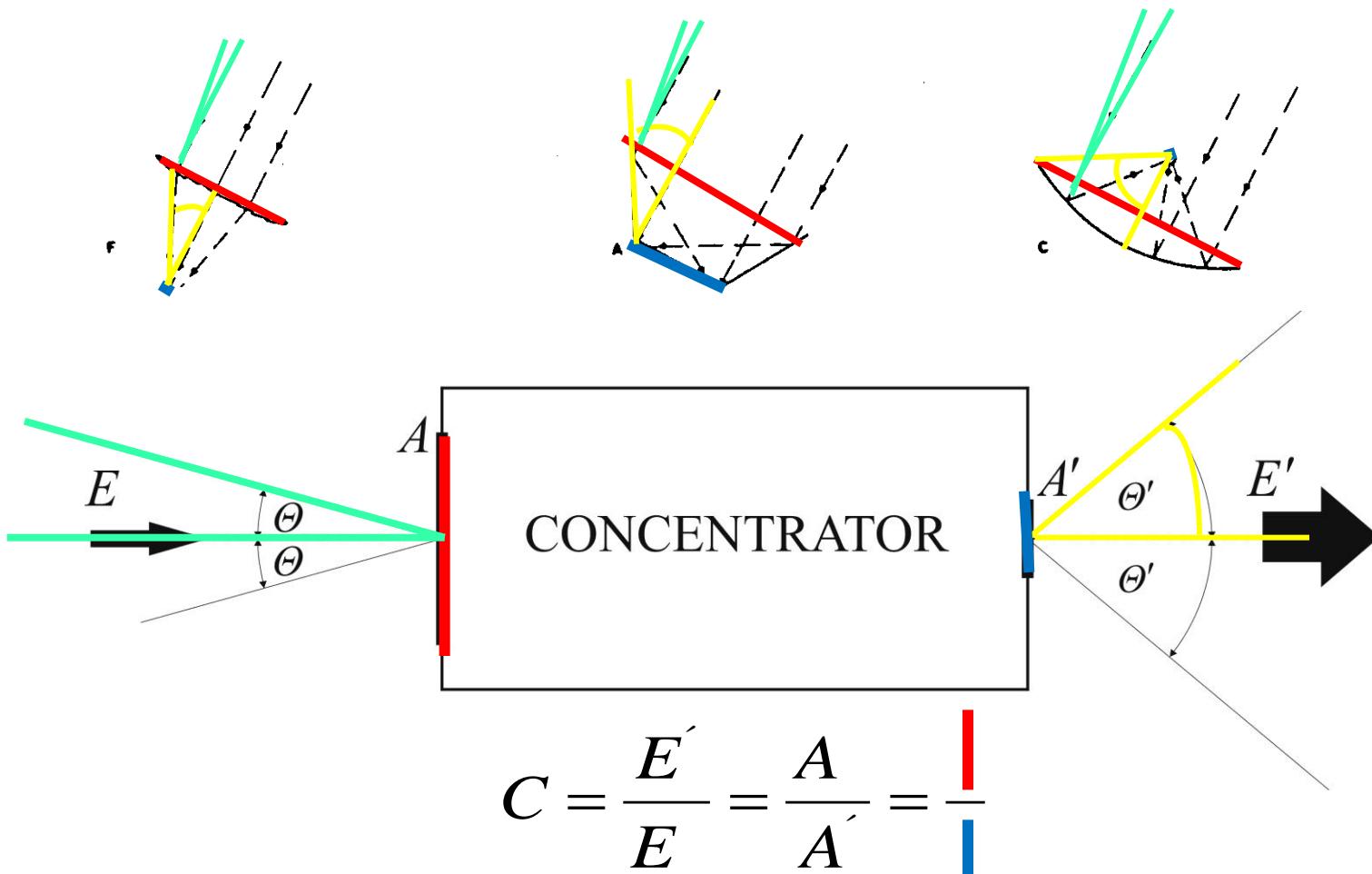


# World solar energy supply ( space: 32 kWh / m<sup>2</sup> / day )

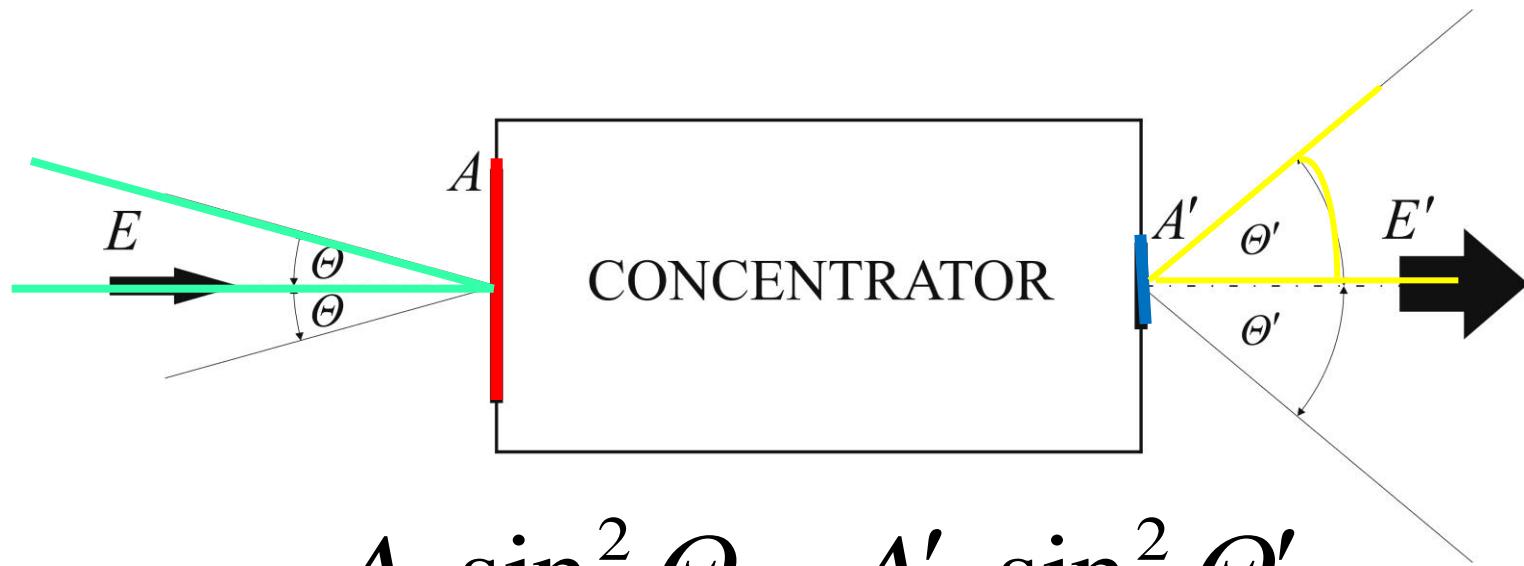
Annual Direct Normal Irradiance (RETScreen-type)  
July 1983 – June 1993



# How to concentrate light?



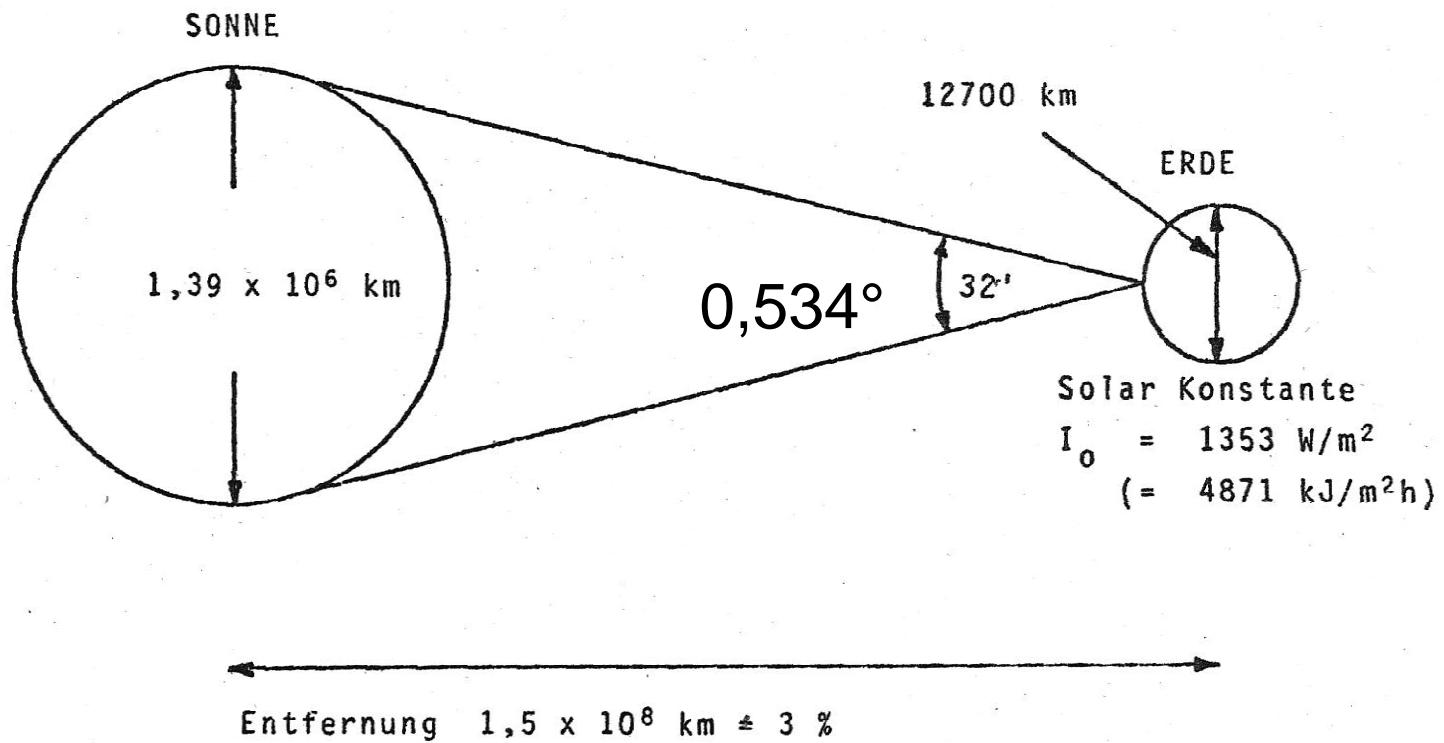
# Conservation of Etendue



$$\underline{A \cdot \sin^2 \Theta} = \underline{A' \cdot \sin^2 \Theta'}$$

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

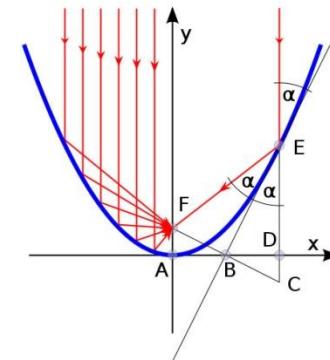
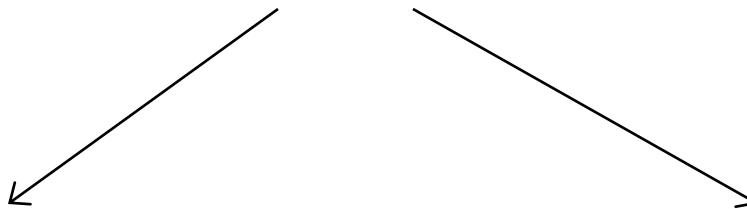
# Maximum Concentration



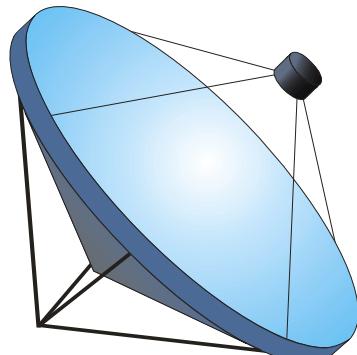
$$C_{\max,3D} = \frac{A}{A'} = \frac{\sin^2 90^\circ}{\sin^2 0,267^\circ} \approx 46200$$

# Radiation concentration on parabolic mirrors

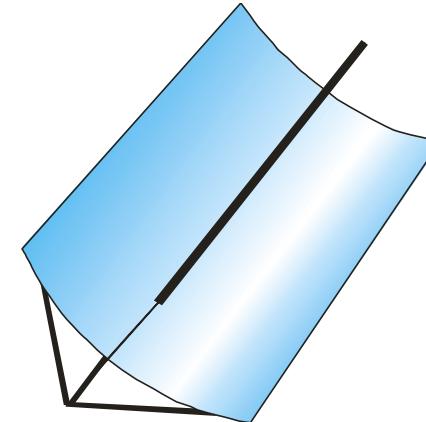
Parabolic mirrors have focal points



Point-focusing: paraboloid mirror

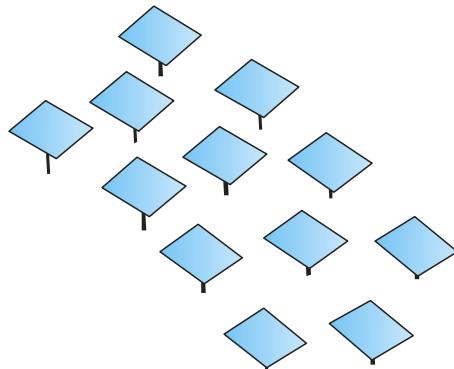


Line-focusing: parabolic troughs

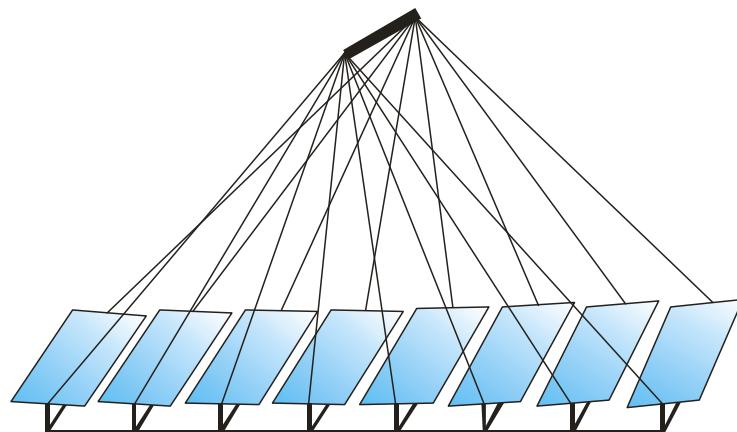


# Alternative concentrating geometries

Point-focusing: heliostat field (solar tower plants)



Line-focusing: Fresnel mirror



# Maximum mean concentration on paraboloid mirrors

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

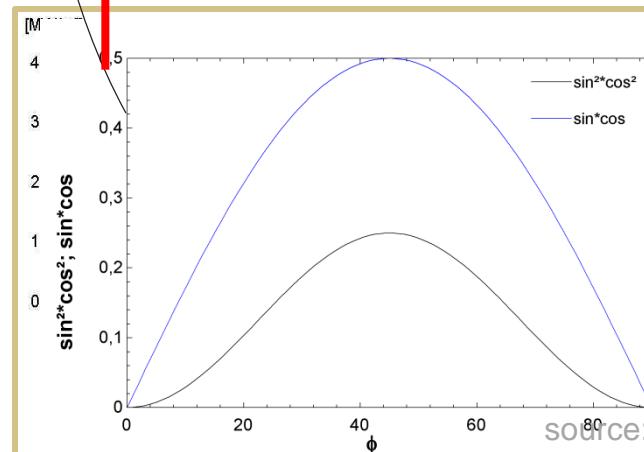
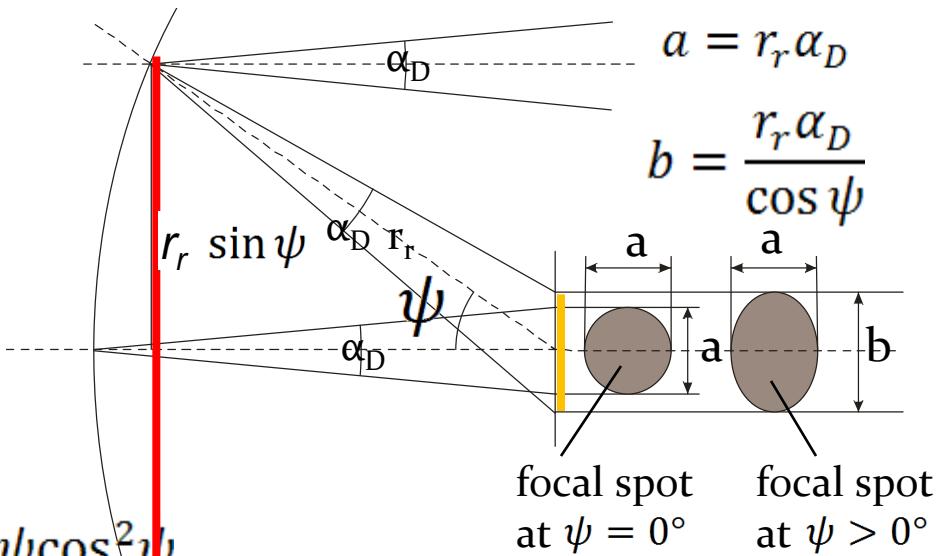
A<sub>ap</sub> ... aperture area  
 A<sub>im</sub> ... image area

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

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

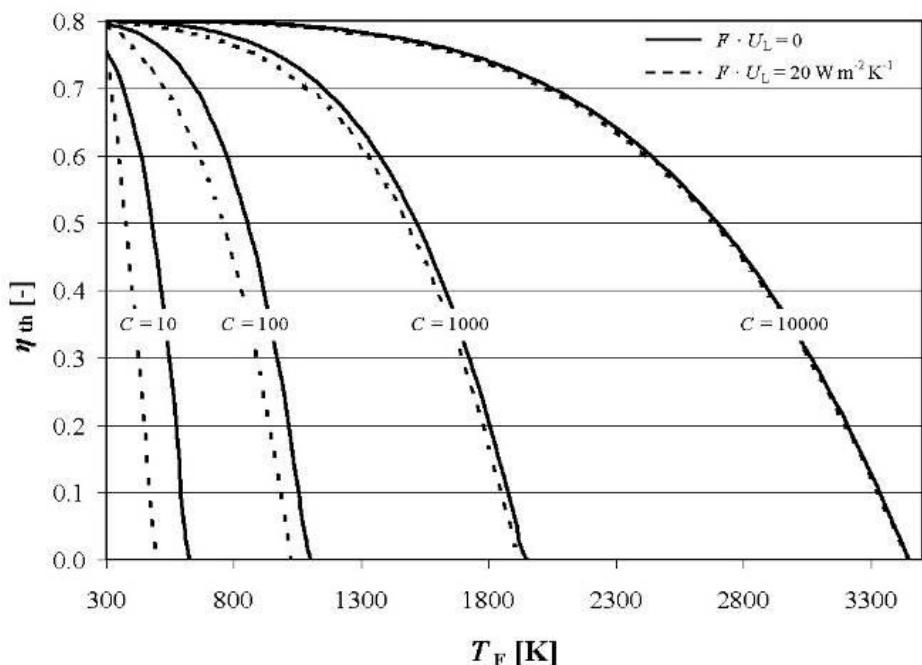
$$C = \frac{1}{\alpha_D^2} \sin^2 \psi \cos^2 \psi = 46200 \sin^2 \psi \cos^2 \psi$$

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



centration  
il at the  
al plane

# Maximum absorber temperature



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

- 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

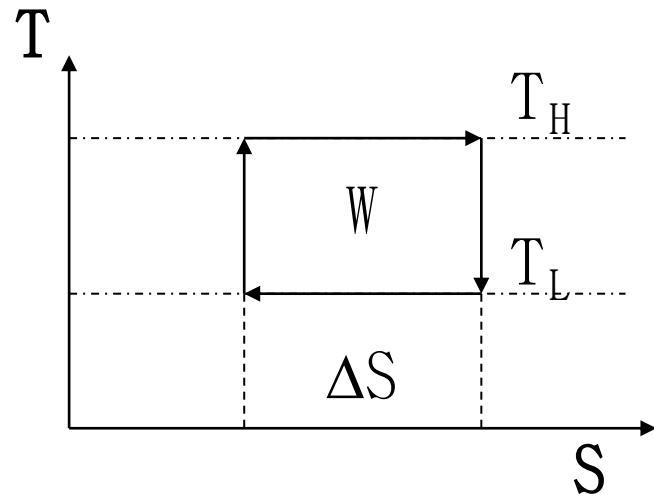
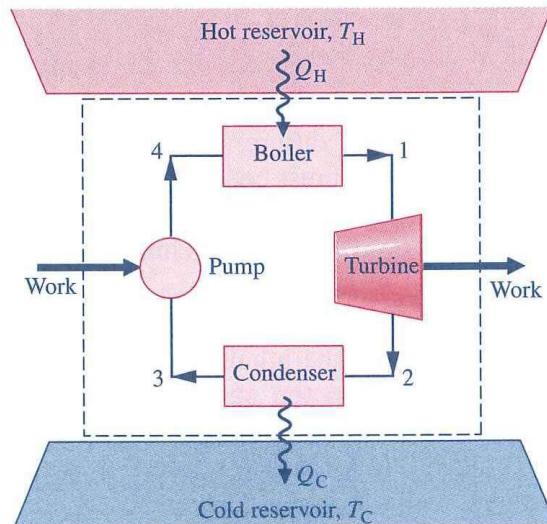
$$Q = \int T dS$$

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

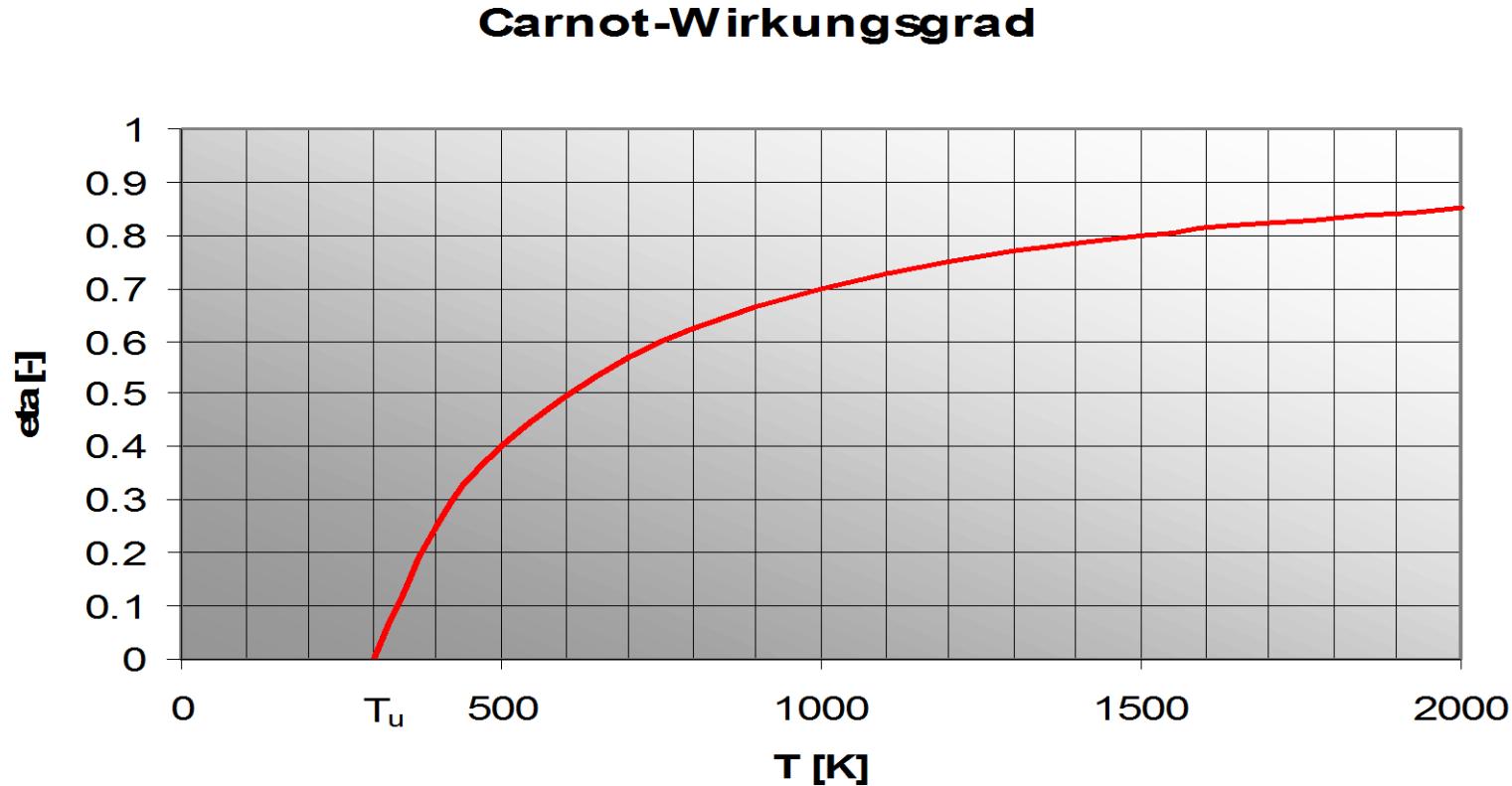
$$Q_{ab} = T_L \Delta S$$

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

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

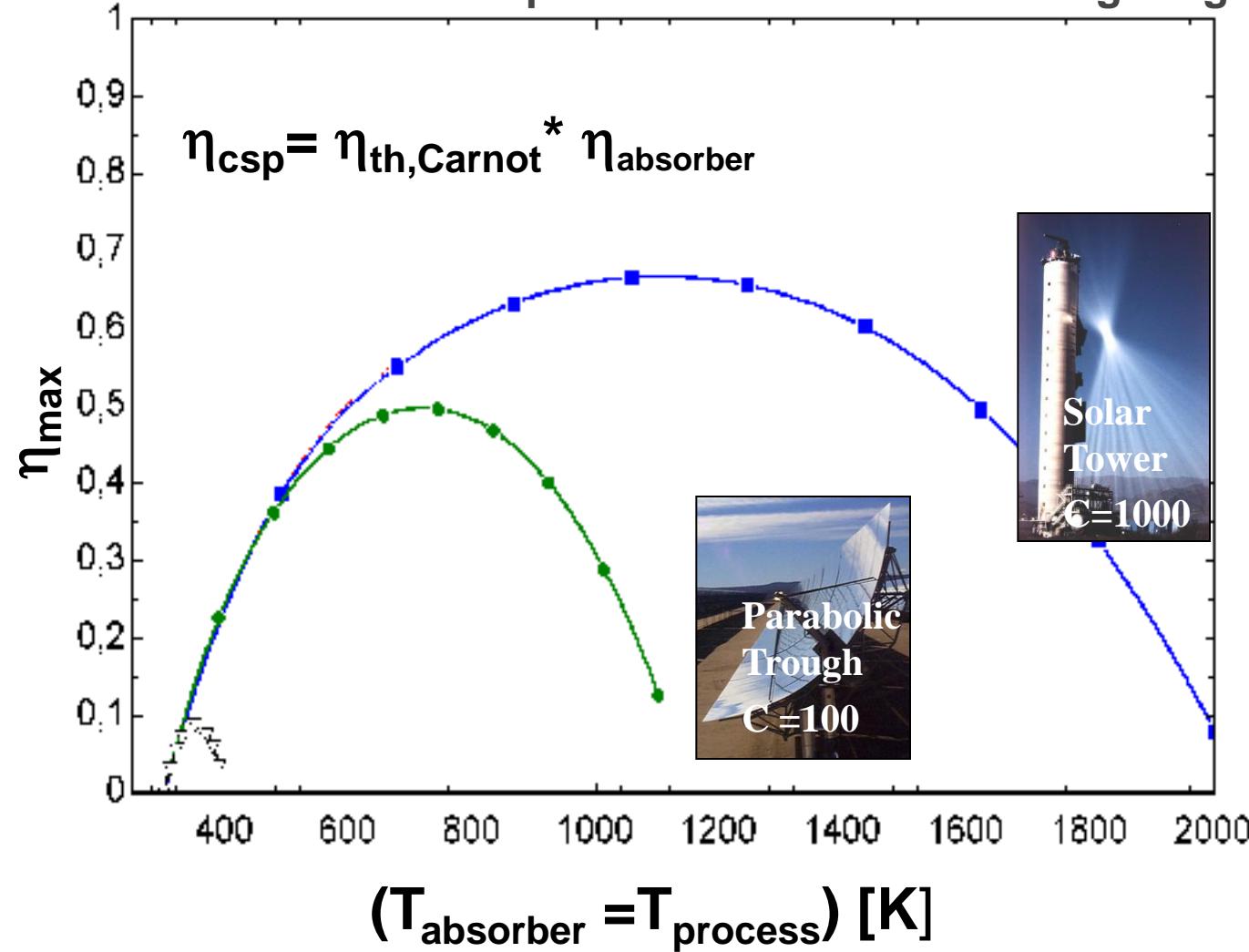


# Efficiency of a Carnot Cycle

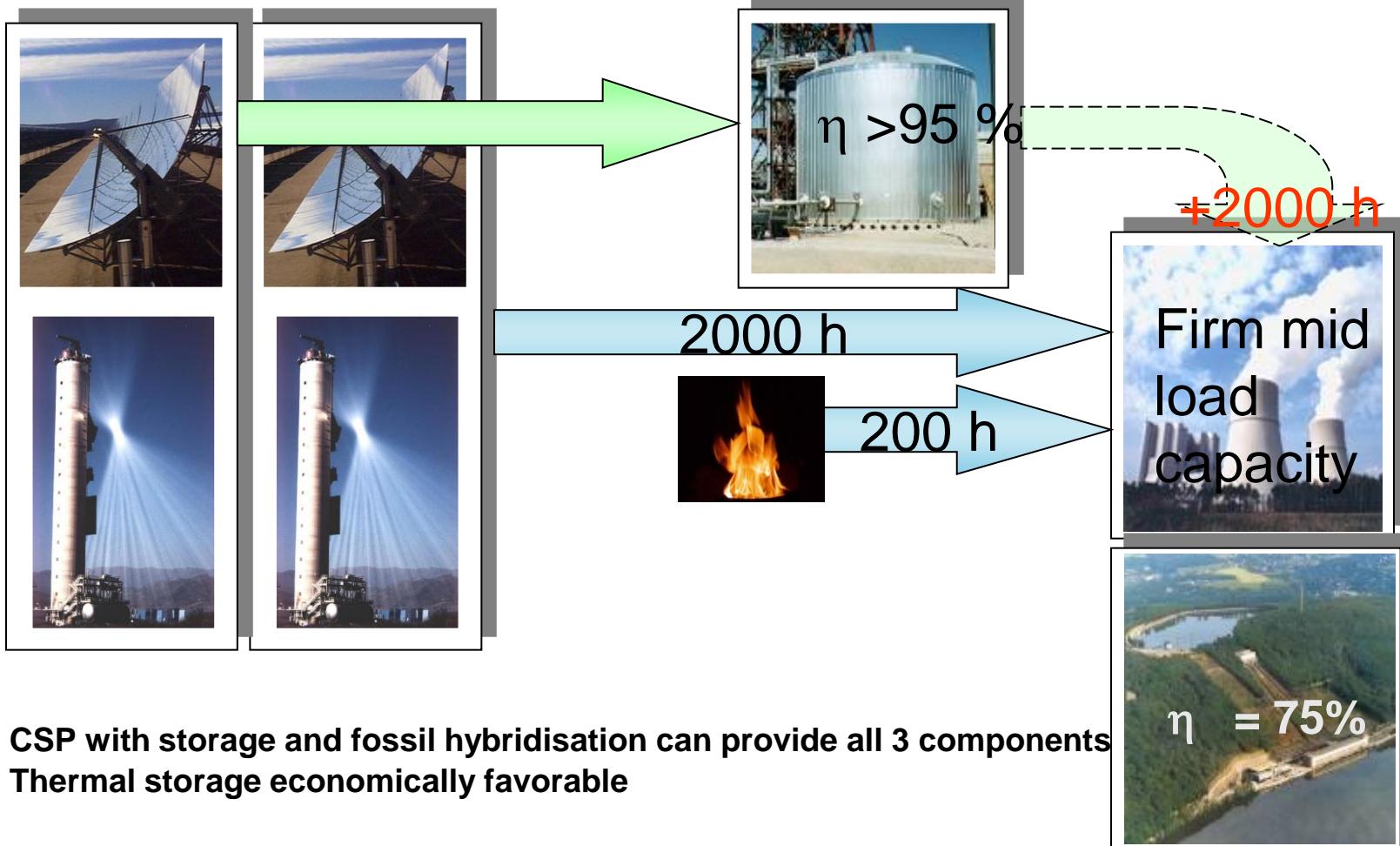


# CSP F&E Strategie:

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



# Thermal Storage vs. Electric Storage



# Types of Concentrating Solar Thermal Technologies



**Solar Power Tower**



**Parabolic Trough**

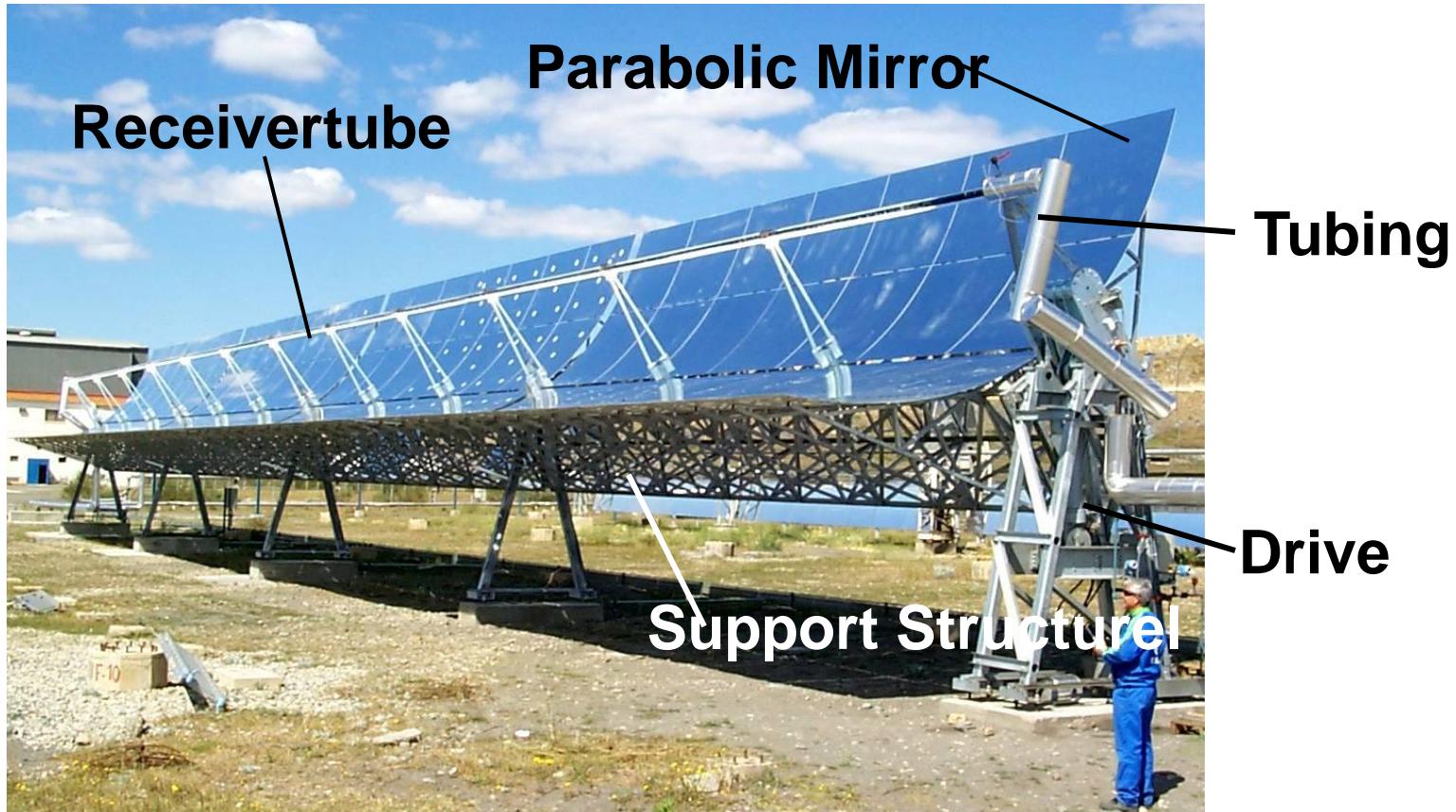


**Linear Fresnel**

# Principle of Parabolic Trough Collector

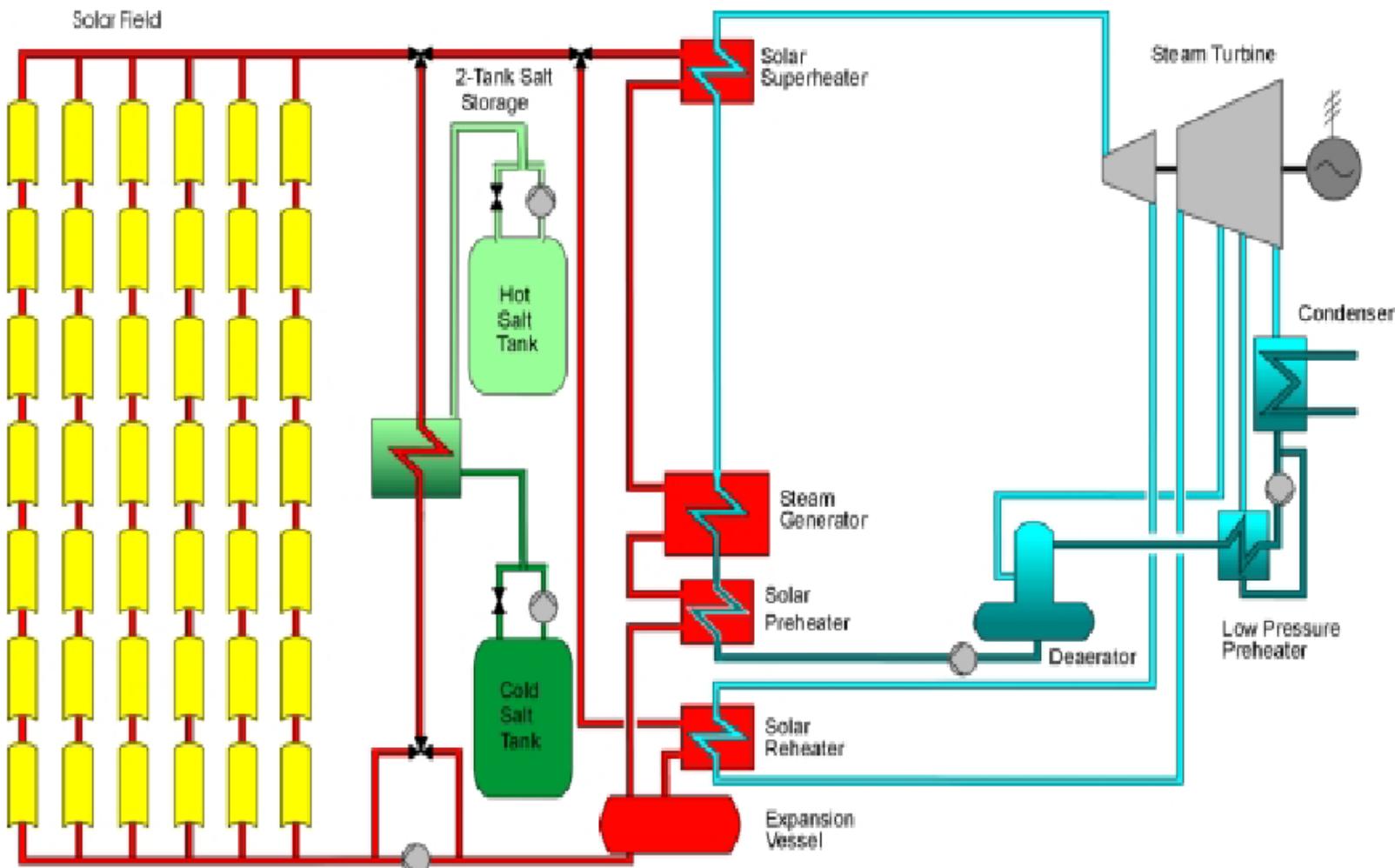


## Collector Components



**Eurotrough-Collector**

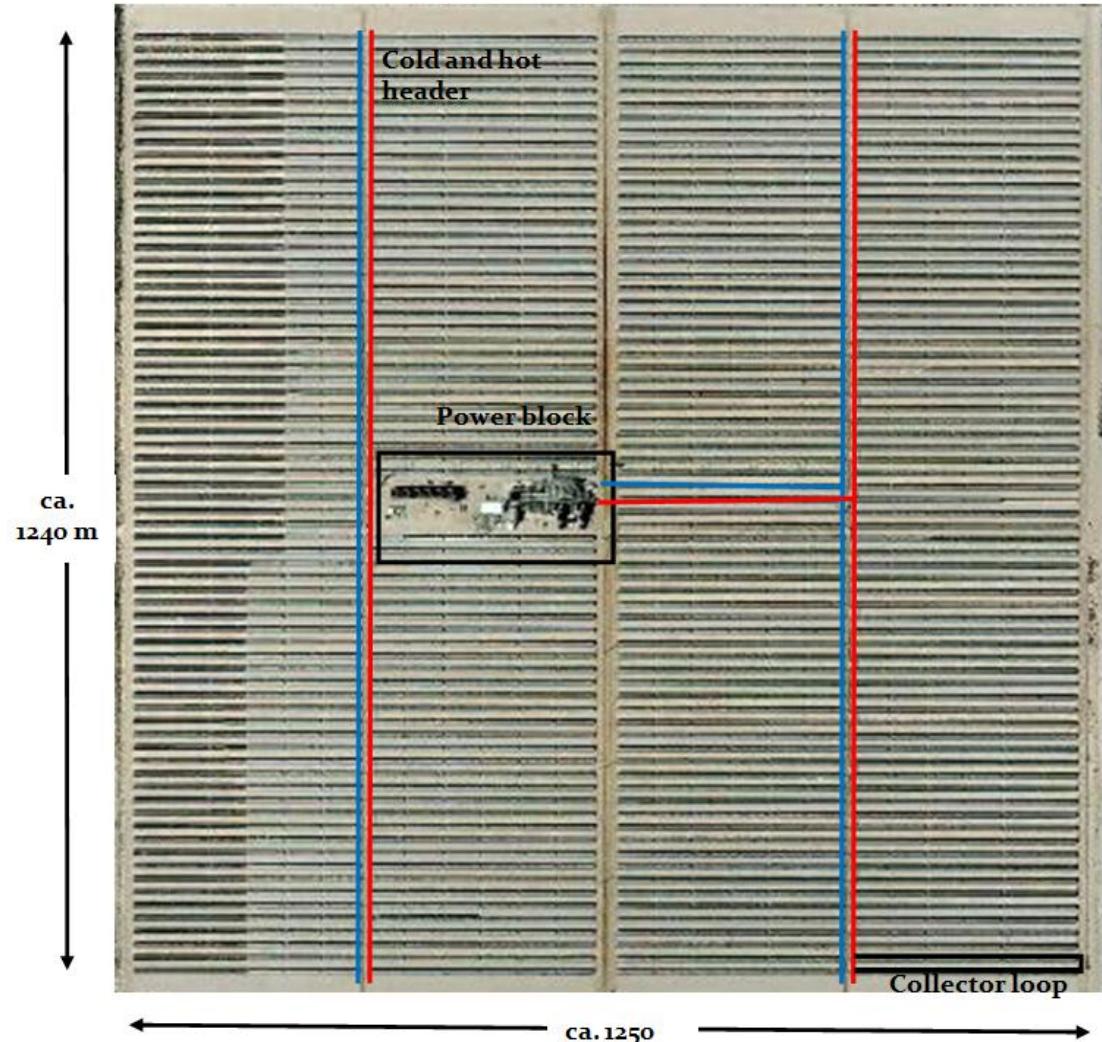
# ANDASOL I



# Solar field: structure

- normally rectangular, nearly square
  - power block near the power plant area centre
- shorter pipes → lower thermal losses

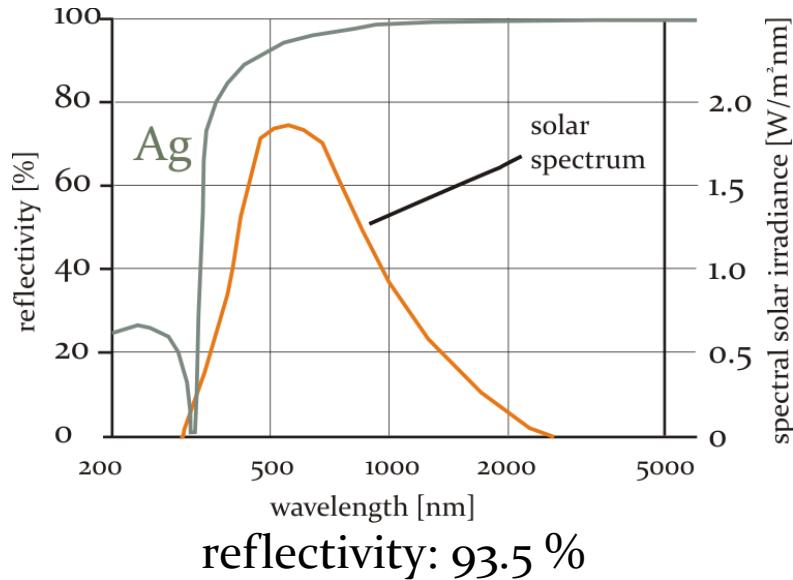
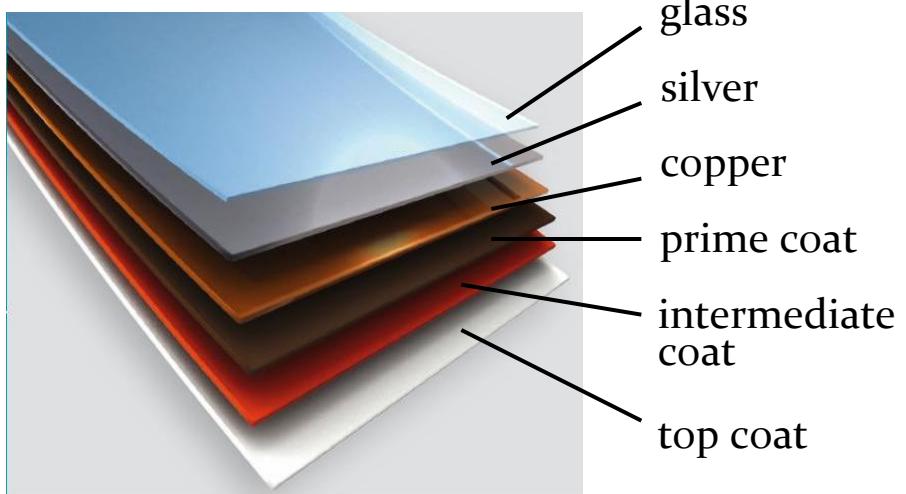
Trough loops are connected to headers, which connect them to the power block.



# Mirror material – silver coated glass mirrors



- used in all realized parabolic trough power plants
- proven technology
- no significant decrease of reflectivity over time



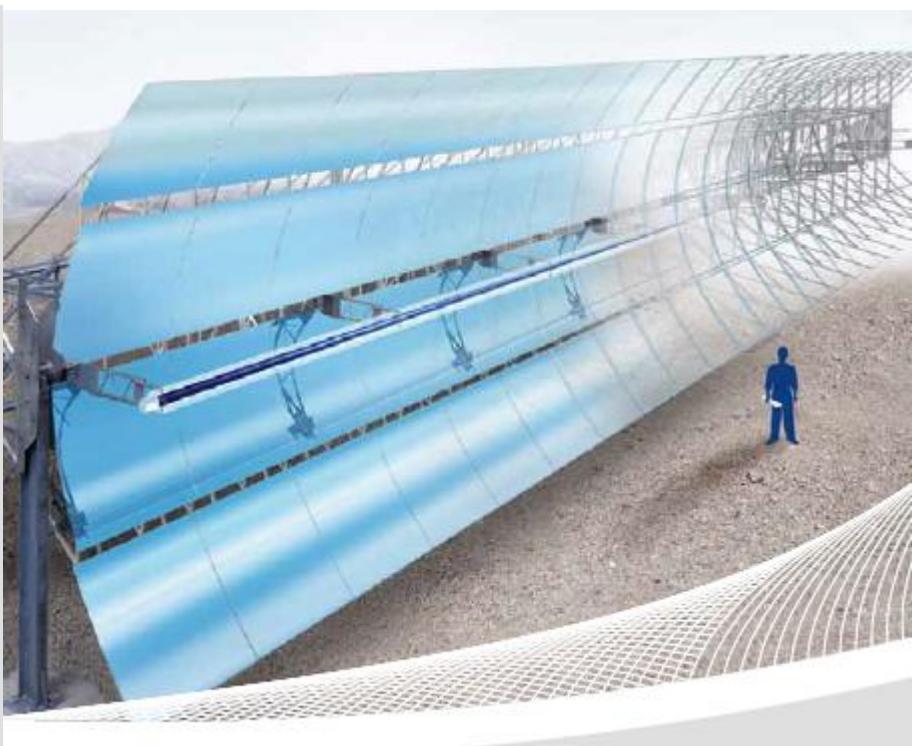
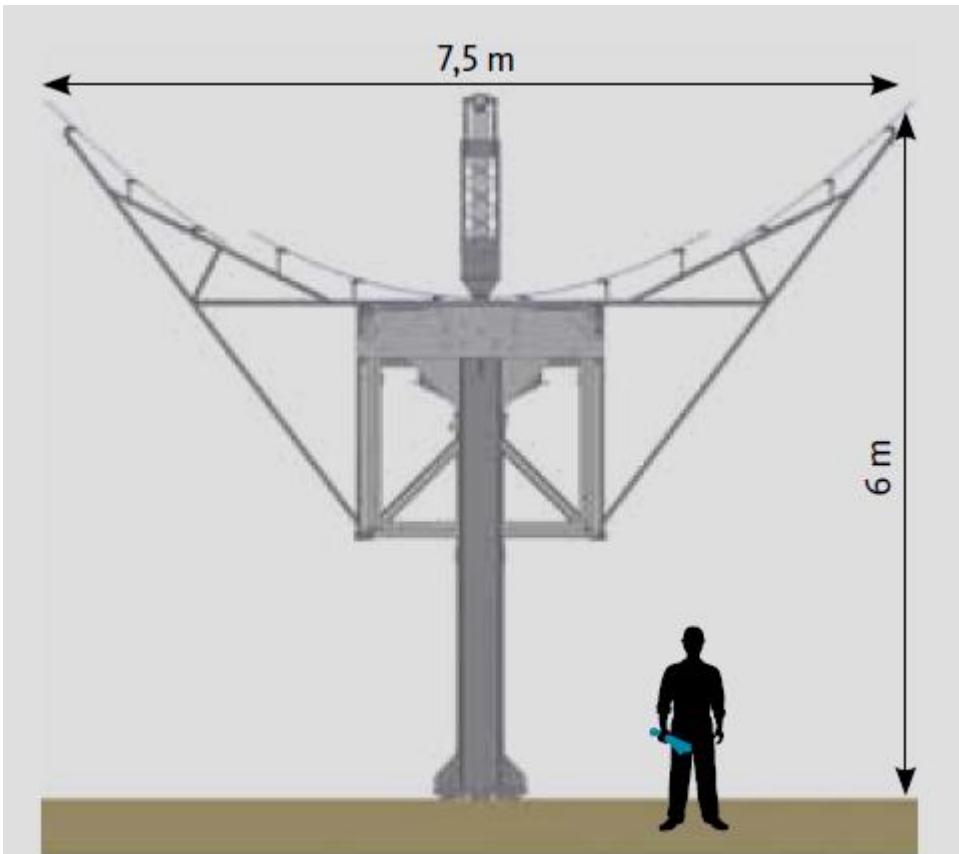
source: CSP Services, Schott

# Bearing structure



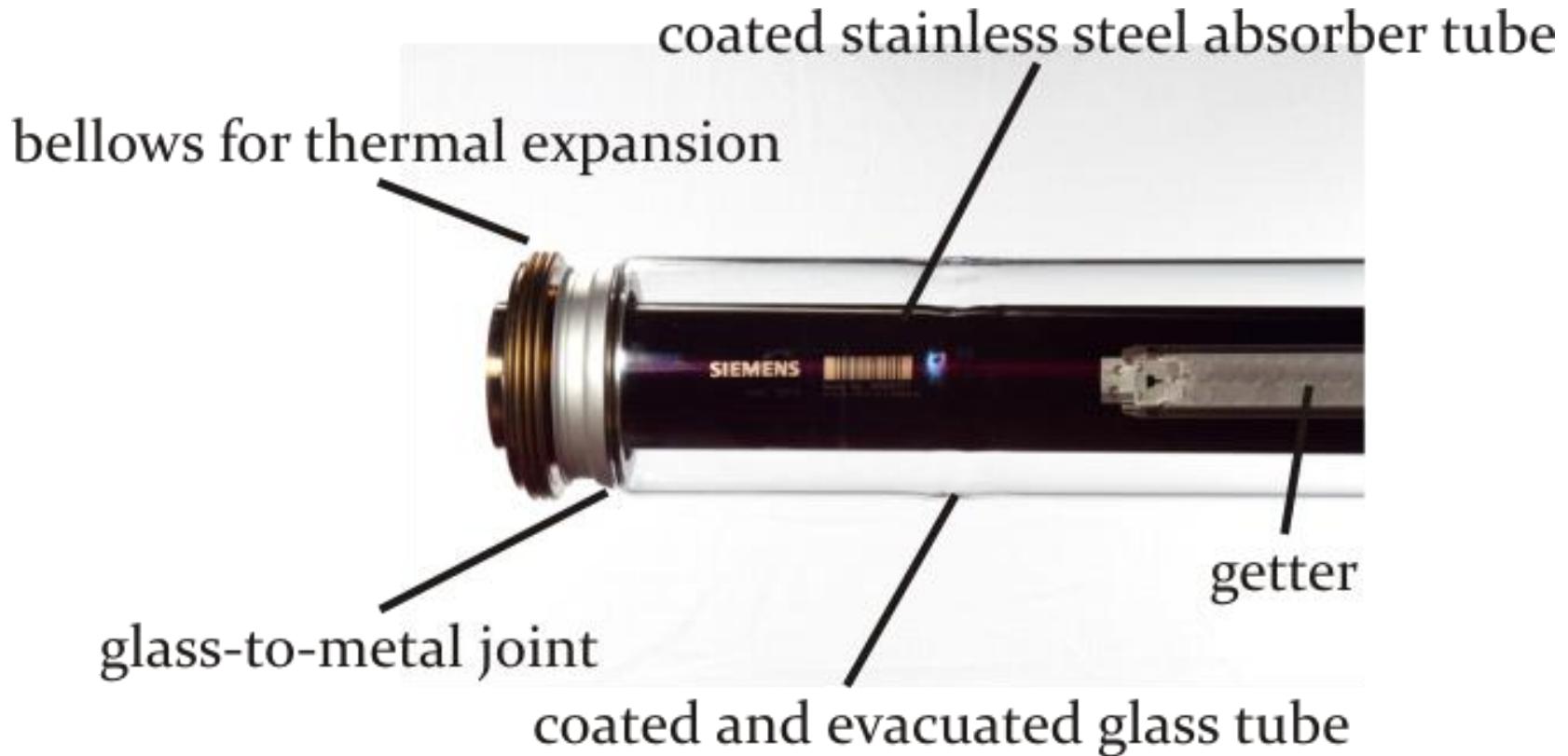
source: Lüpfert, DLR, ENEA

# Ultimate Trough Development



Dimensions of one Solar Collecting Element (SCE).  
One Solar Collector Assembly (SCA) consists of ten SCEs.

# Receiver components



source: [www.energy.siemens.com](http://www.energy.siemens.com)

# Further important components

thermal expansion of the receiver



**bellows** for thermal absorber tube expansion

vacuum sealed **glass-to-metal joints**

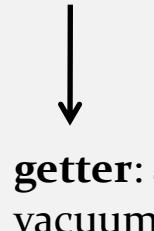
glass and metal must have the same thermal expansion coefficient

bellows for thermal expansion

glass-to-metal joint

getter

hydrogen may diffuse through the absorber tube

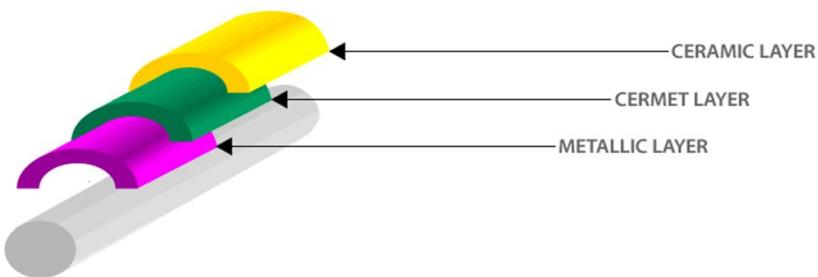


source: Siemens

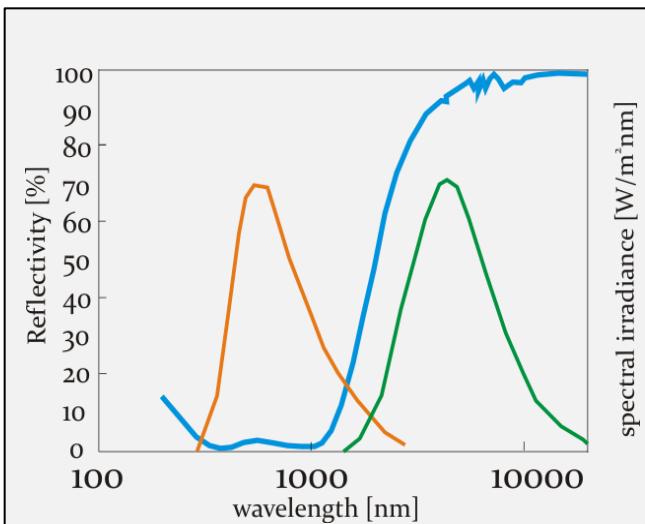
# Absorber tube

- high absorptance in the solar spectrum
  - low emissivity in the infrared range
- selective coating

multilayer coatings:



- metal layer (e.g. Cu, Al, Mo) for infrared reflection
- cermet layer (combination of ceramic material and metal) for high absorptivity
- ceramic antireflection layer



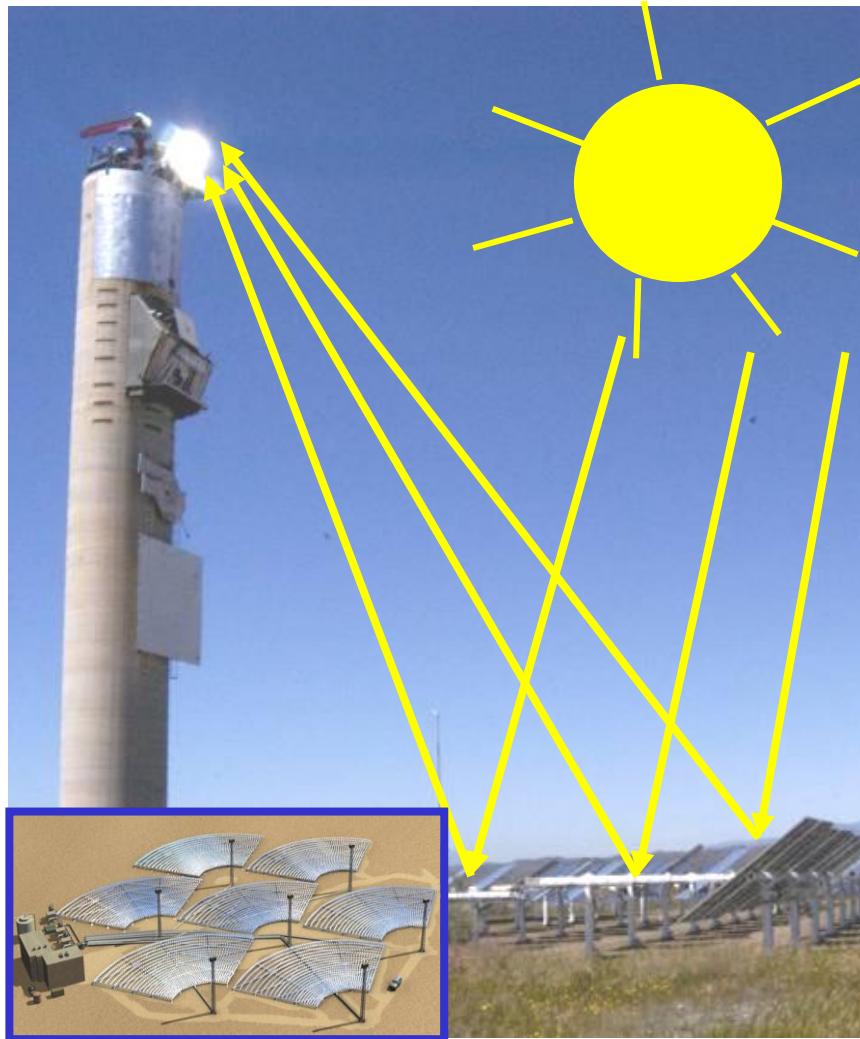
absorptance (= 1 – reflectivity)  
of a selective coating

- solar radiation spectrum
- thermal radiation spectrum at 400°C

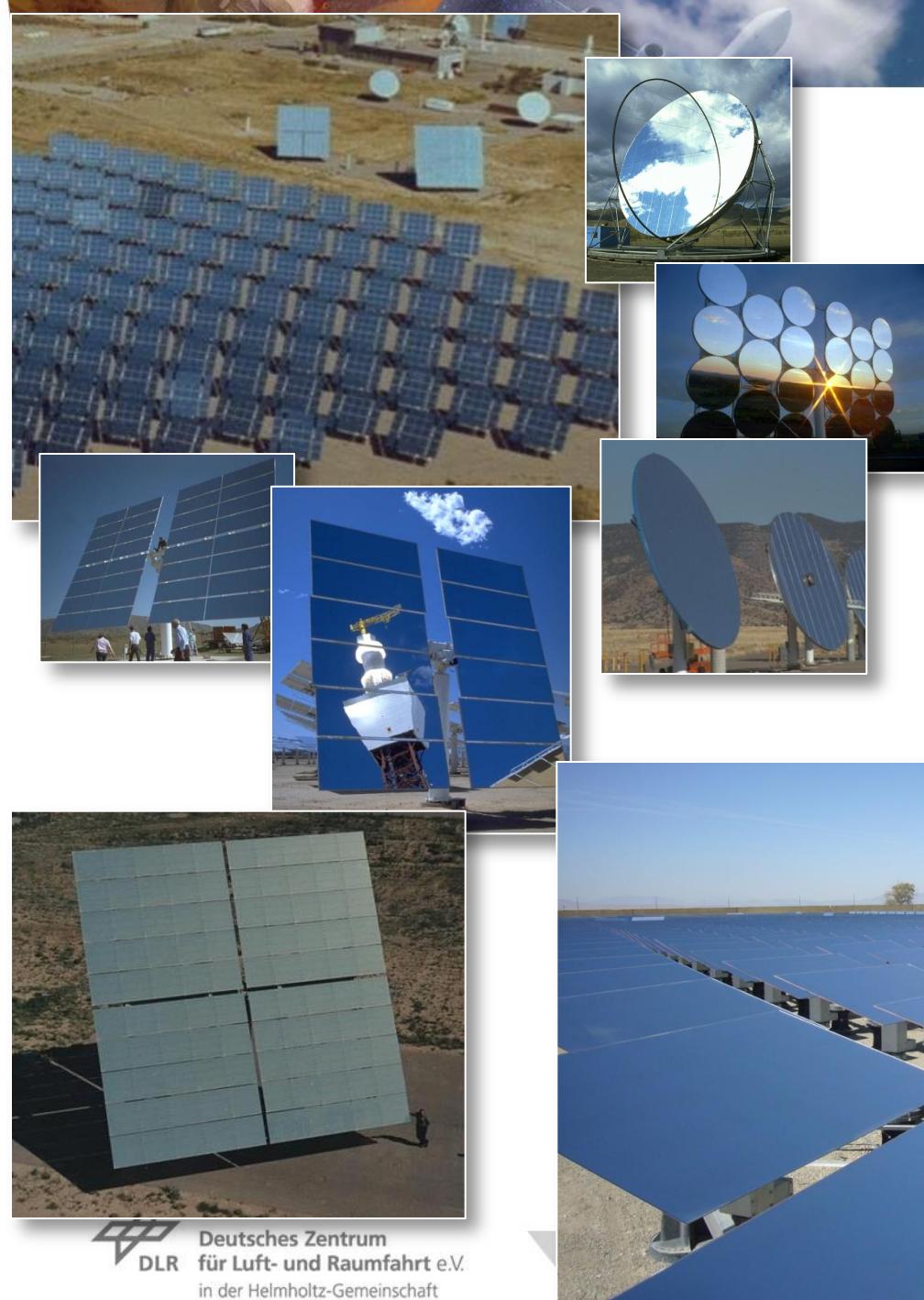
source: [www.archimedesolarenergy.com](http://www.archimedesolarenergy.com)

# 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



# Heliostats





# Typical design of heliostats



# Heliostats



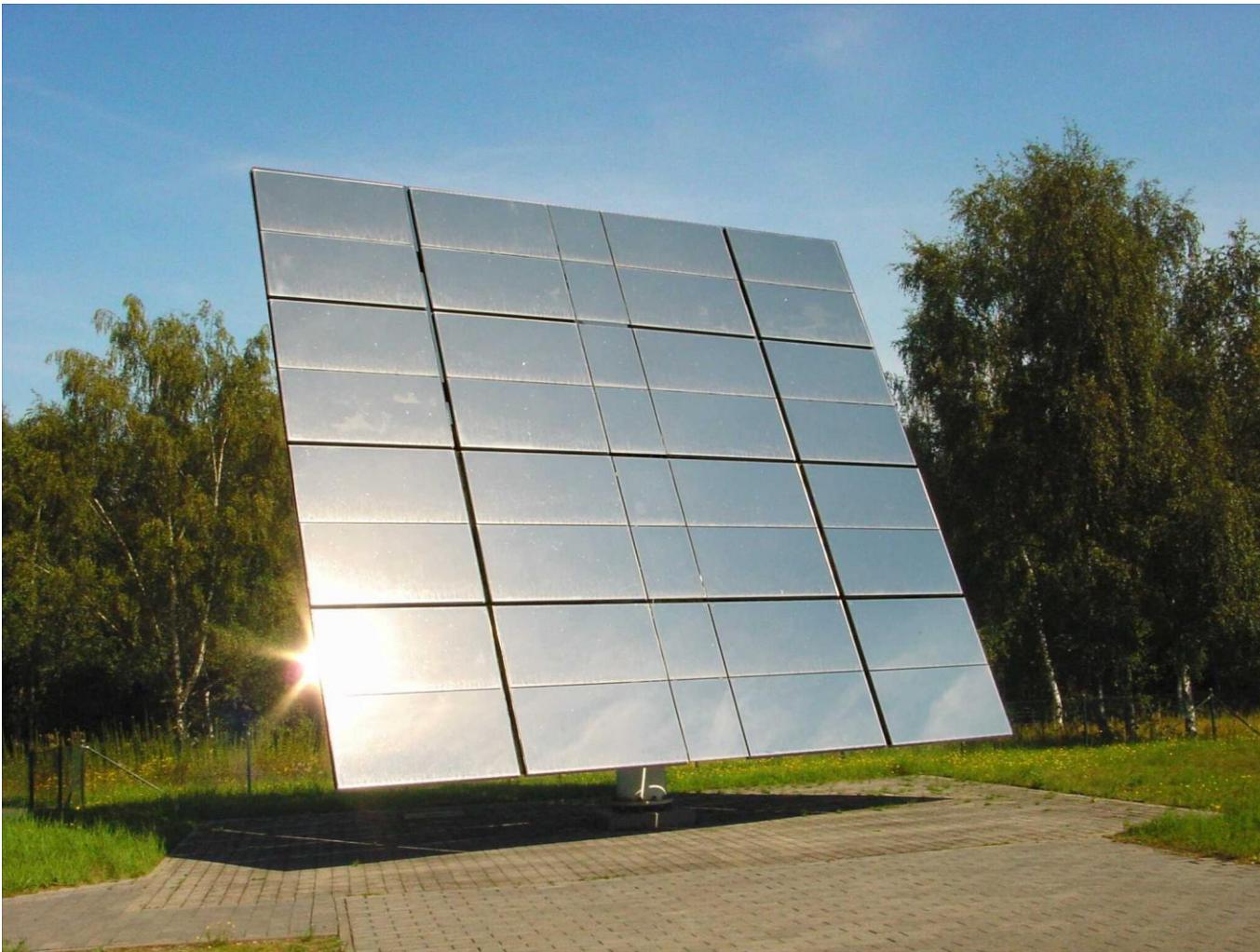
# Metal foil heliostats



# Steinmüller 150 m<sup>2</sup> heliostat



# Heliostat at the DLR solar furnace in Cologne



# 8 Solar Tower Technology

## Heliostat Field Losses

### a) Cosine Loss

Equation for calculating the cosine loss:

$$\text{Cosine loss} = 1 - \cos \beta$$

Radiant power:

$$P_{rad} = I_{dir} A_{eff}$$

with  $A_{eff} = A_{mirr} \cos \beta$

$I_{dir}$ : direct normal irradiation

A: area

eff: effective

mirr: mirror

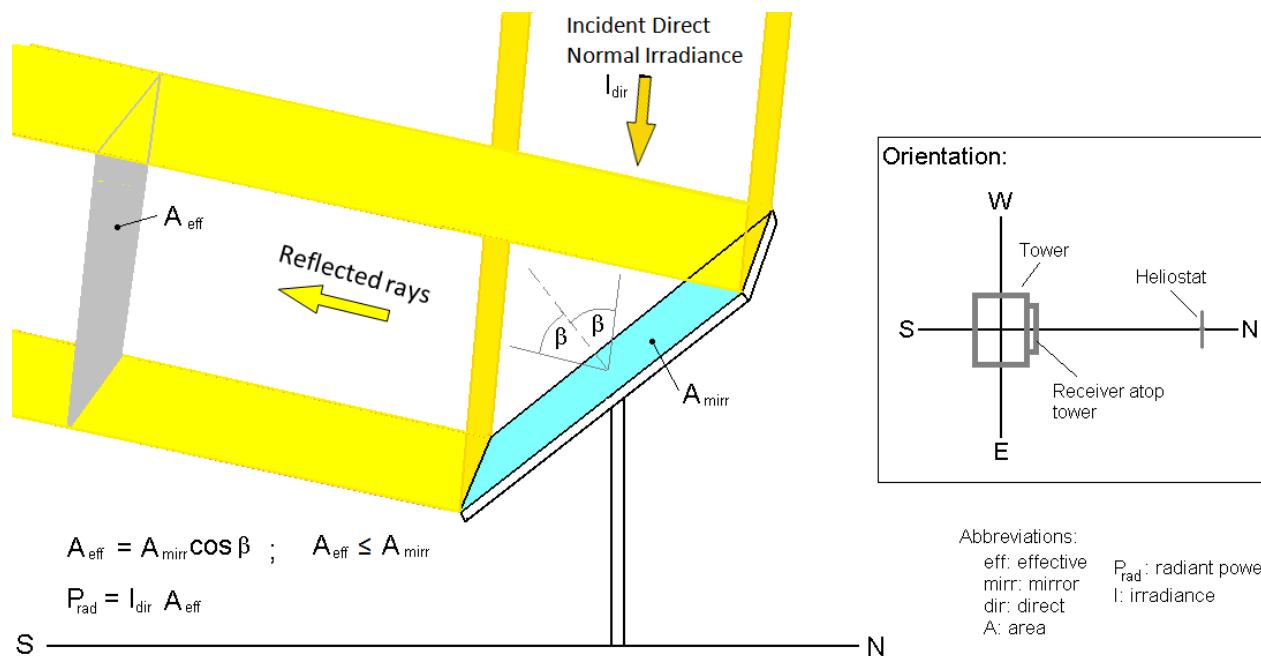


Fig.: Effect of cosine loss on radiant power reflected by heliostat

Sources: [4]

## Heliostat Field Losses

### b) Blocking Loss

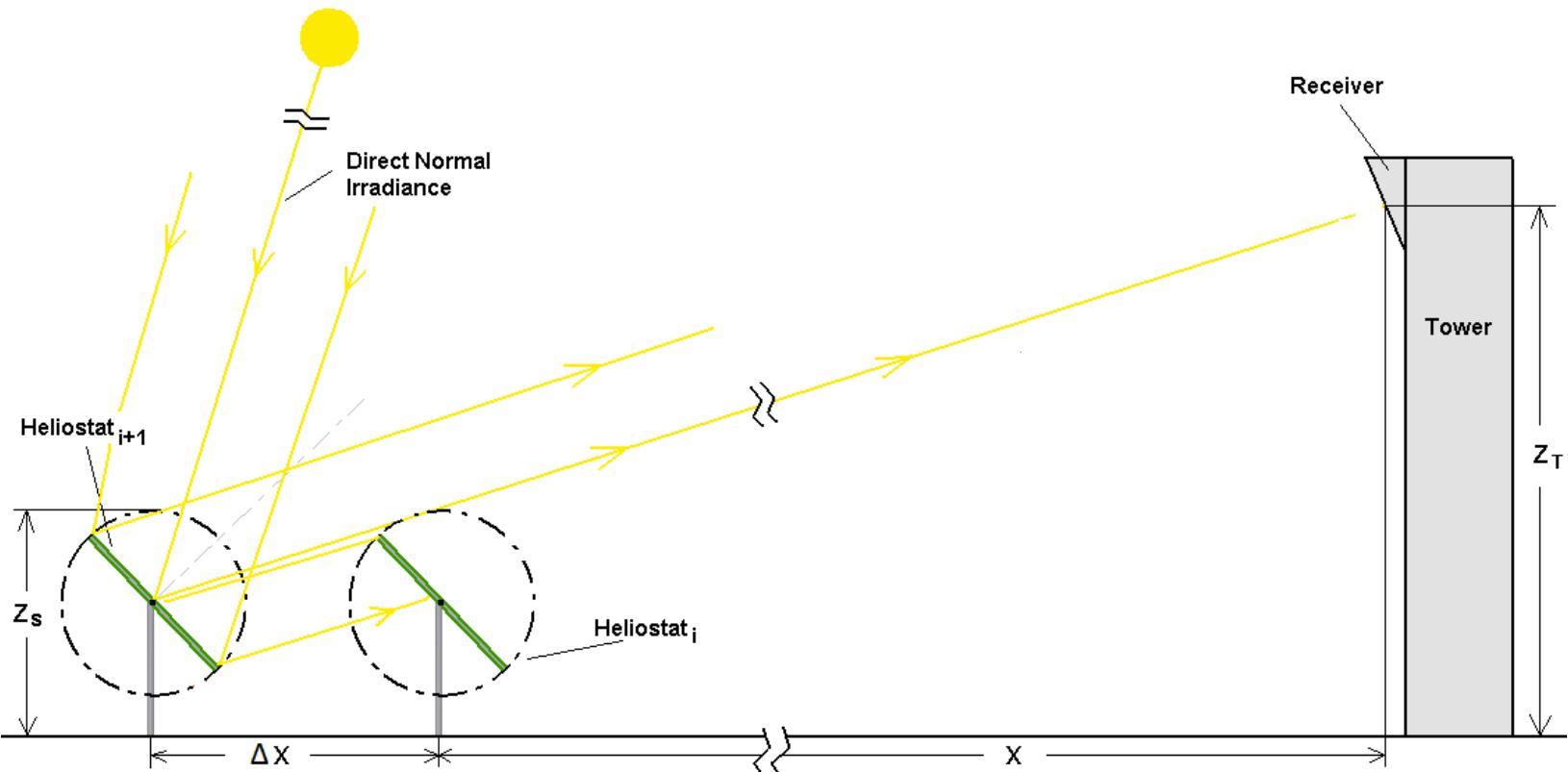


Fig.: Heliostat blocking

Sources: [5]

## Heliostat Field Losses

### c) Shadowing Loss

- Shadowing: a front heliostat casts shadow on a heliostat behind or sideways of it

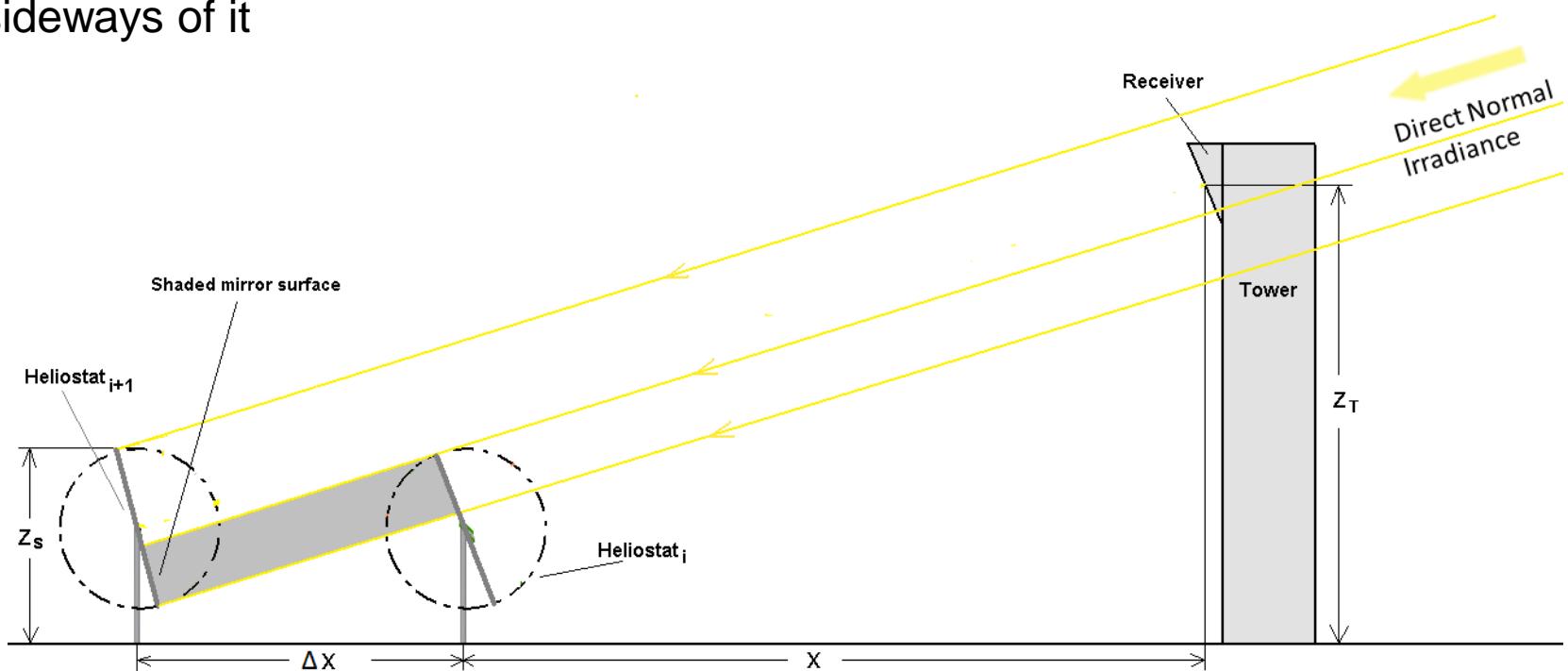


Fig.: Shadowing Loss

## Heliostat Field Losses

### d) Spillage Loss

- ↗ Heliostat field reflects and directs the direct normal irradiance on the receiver surface
- ↗ A portion of the irradiation may miss the receiver surface – this is called spillage
- ↗ Amount of spillage dependent on
  - ↗ tracking accuracy
  - ↗ mirror quality

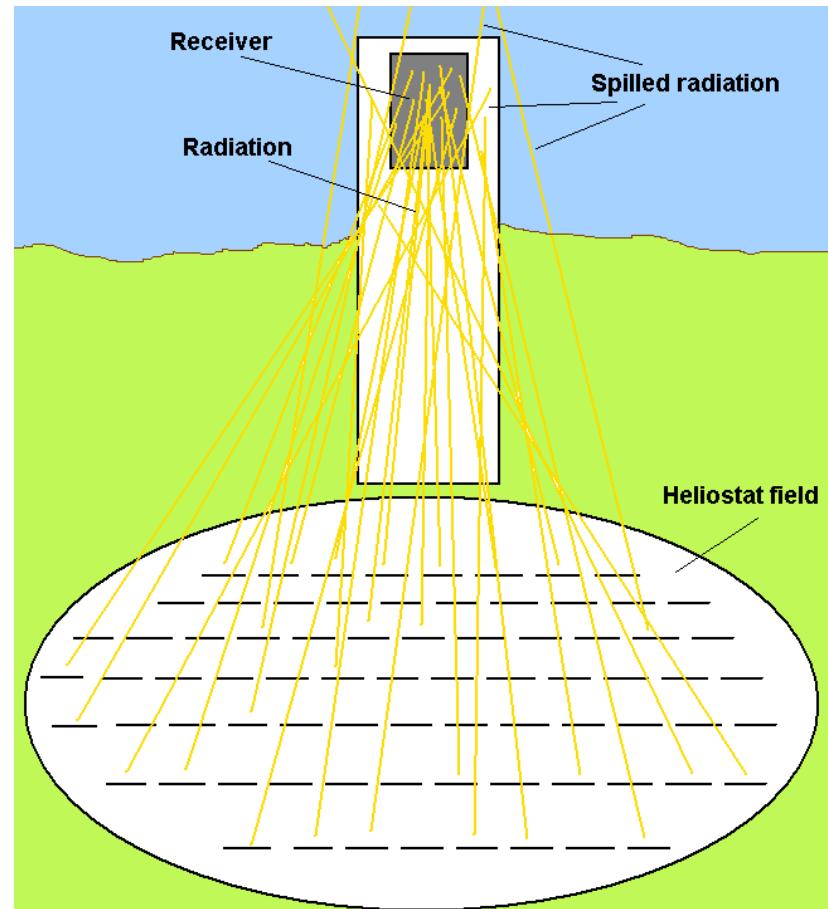


Fig.: Spillage loss

## Heliostat Field Losses

### Calculating optical losses

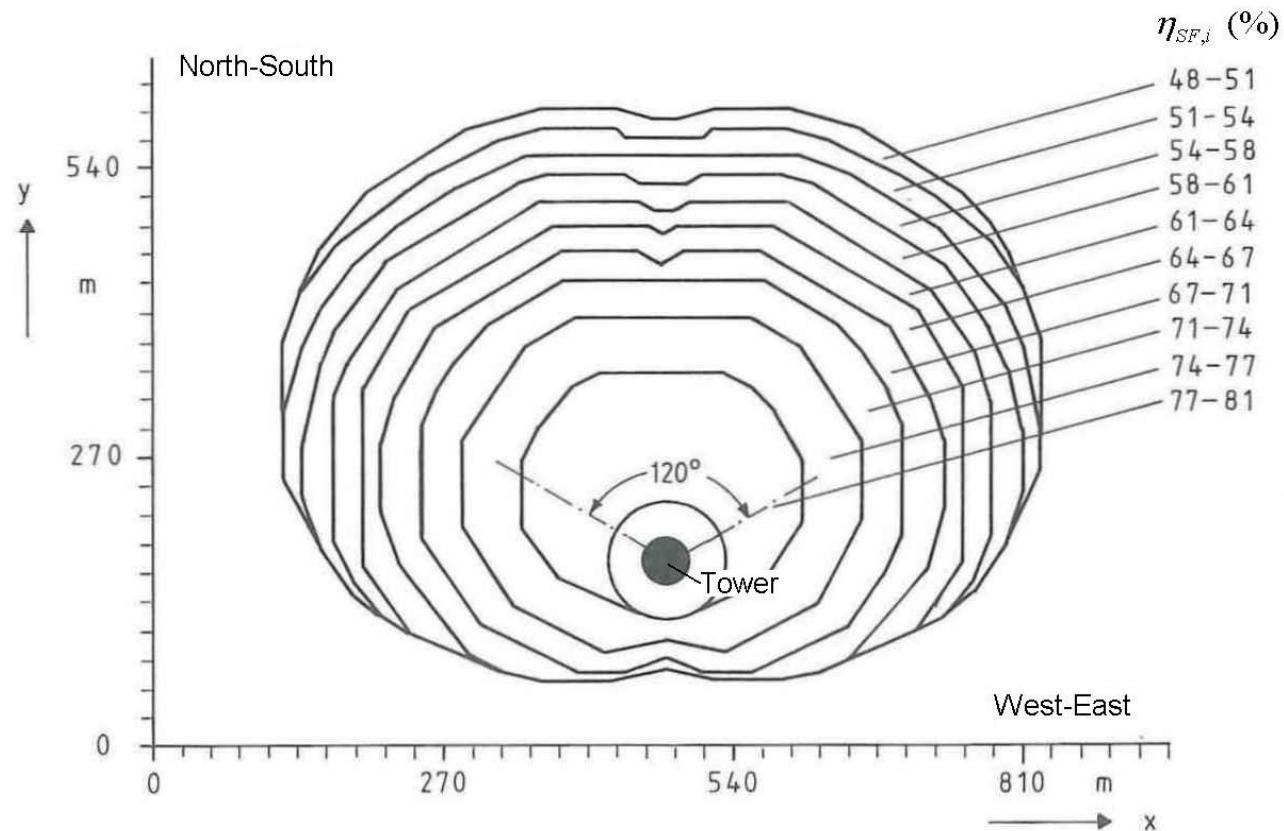
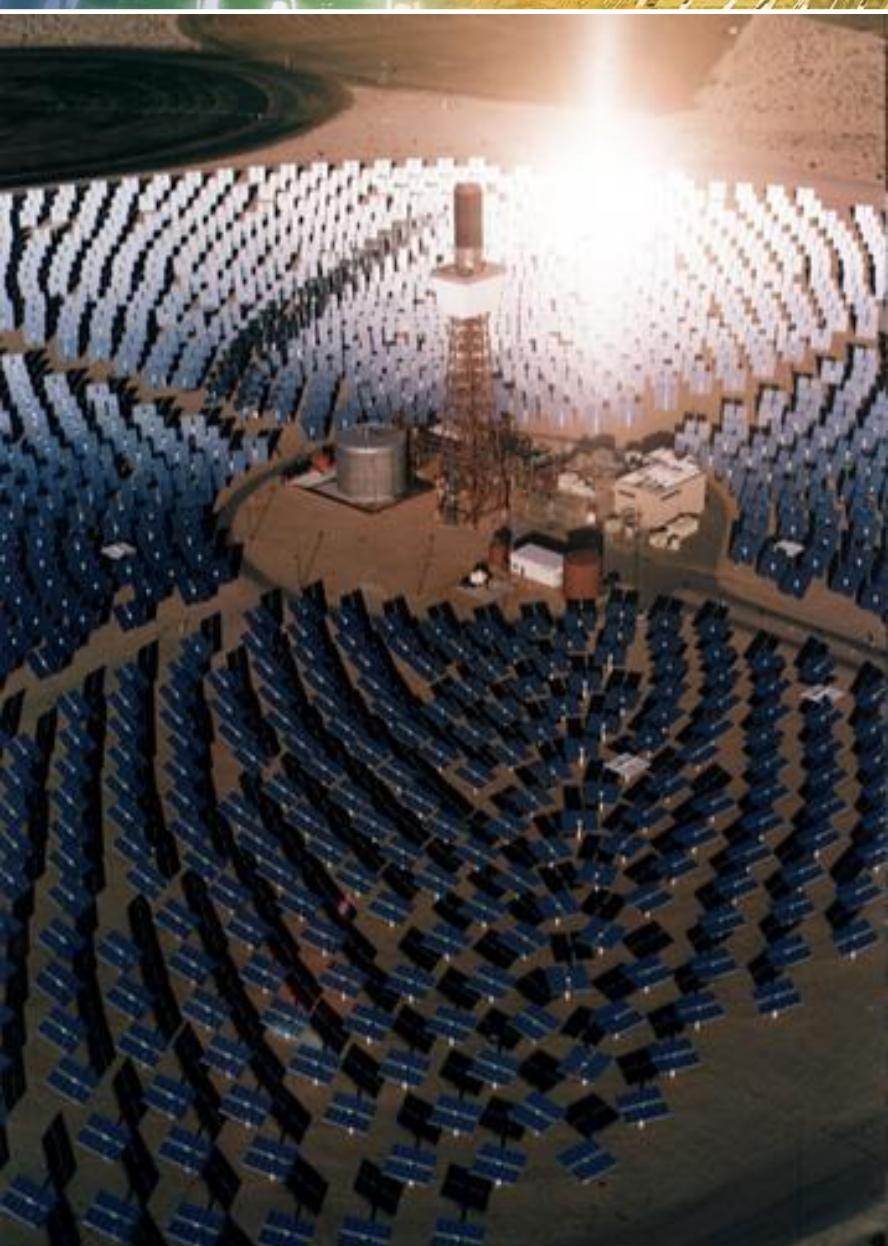


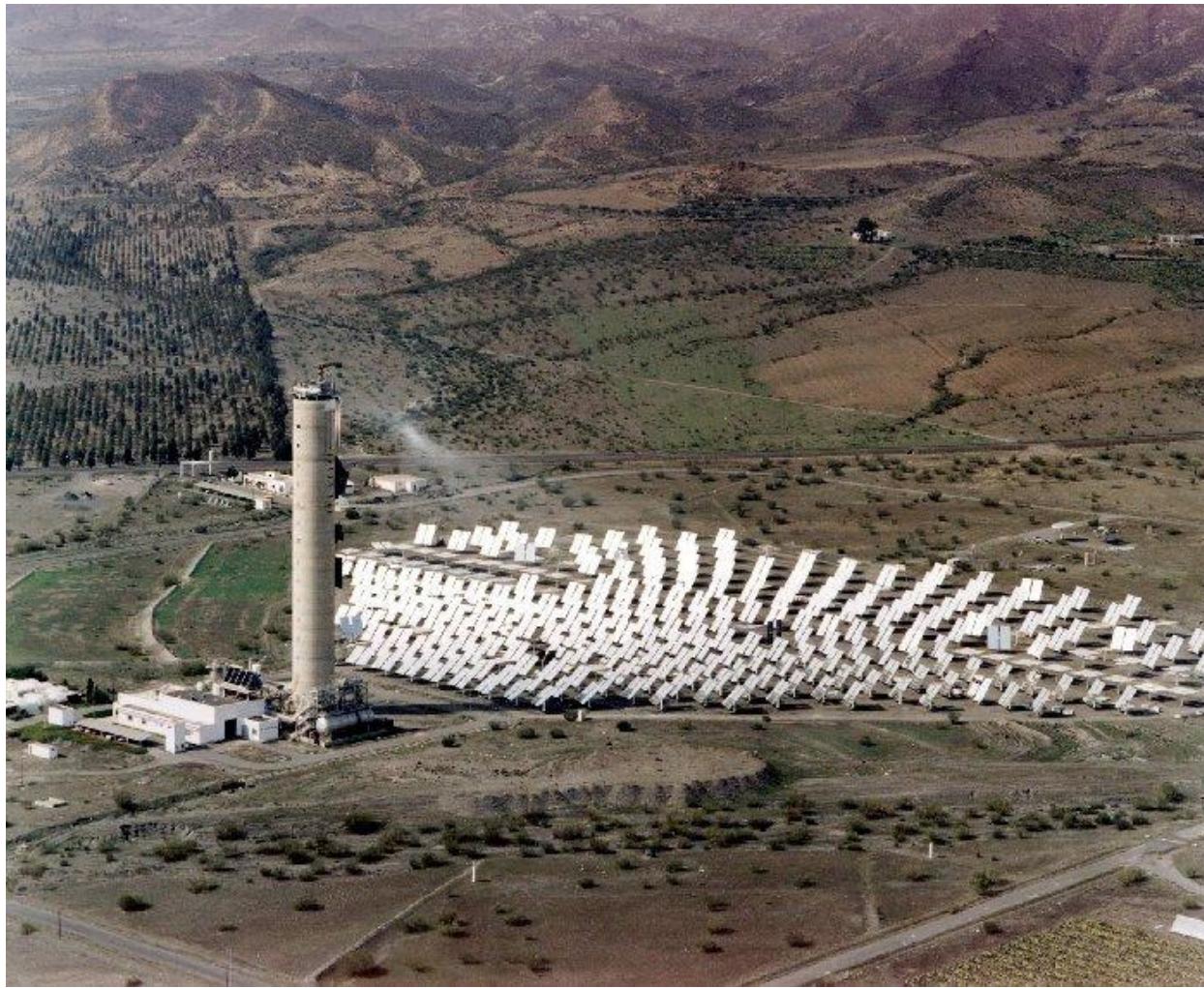
Fig.: Computed efficiency lines of the heliostat field of the 20 MW<sub>e</sub> solar tower plant GAST (according to GAST, 1989)

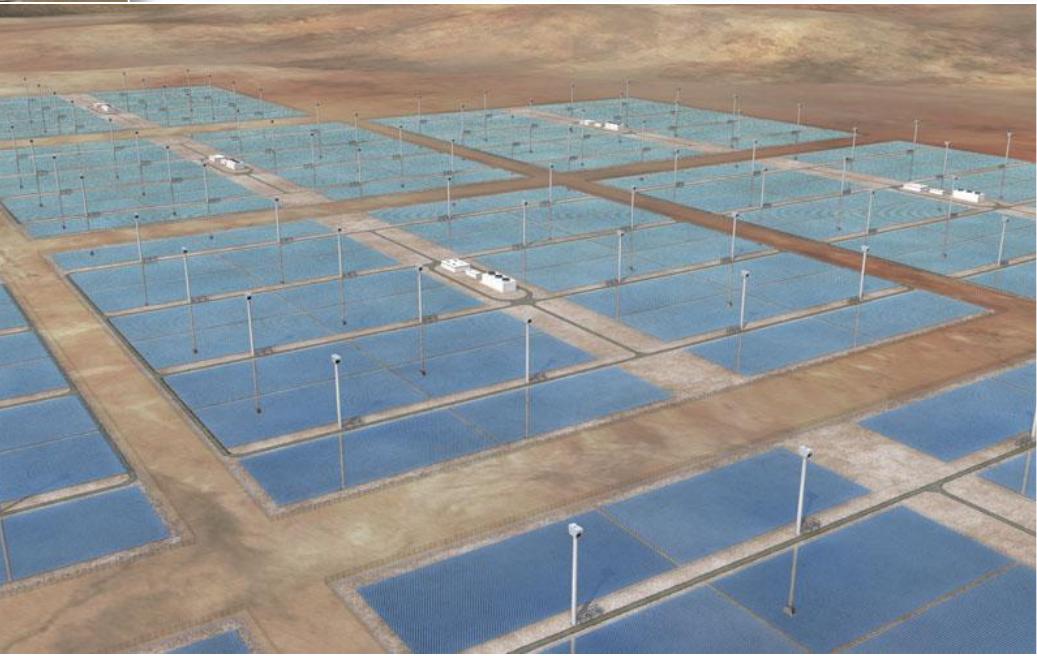
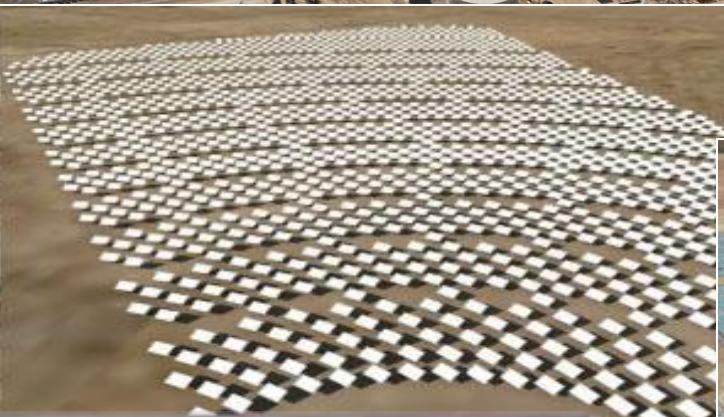


## **Central heliostat arrangement, Solar Two in Barstow, California**



# North field arrangement (Cesa 1 in Almeria, Spain)





# Modularity & Scalability

# Receivers



# Crescent 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 background 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<sup>2</sup>/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



# Crescent Dunes

(100 MW Molten Salt, 6 h Storage)

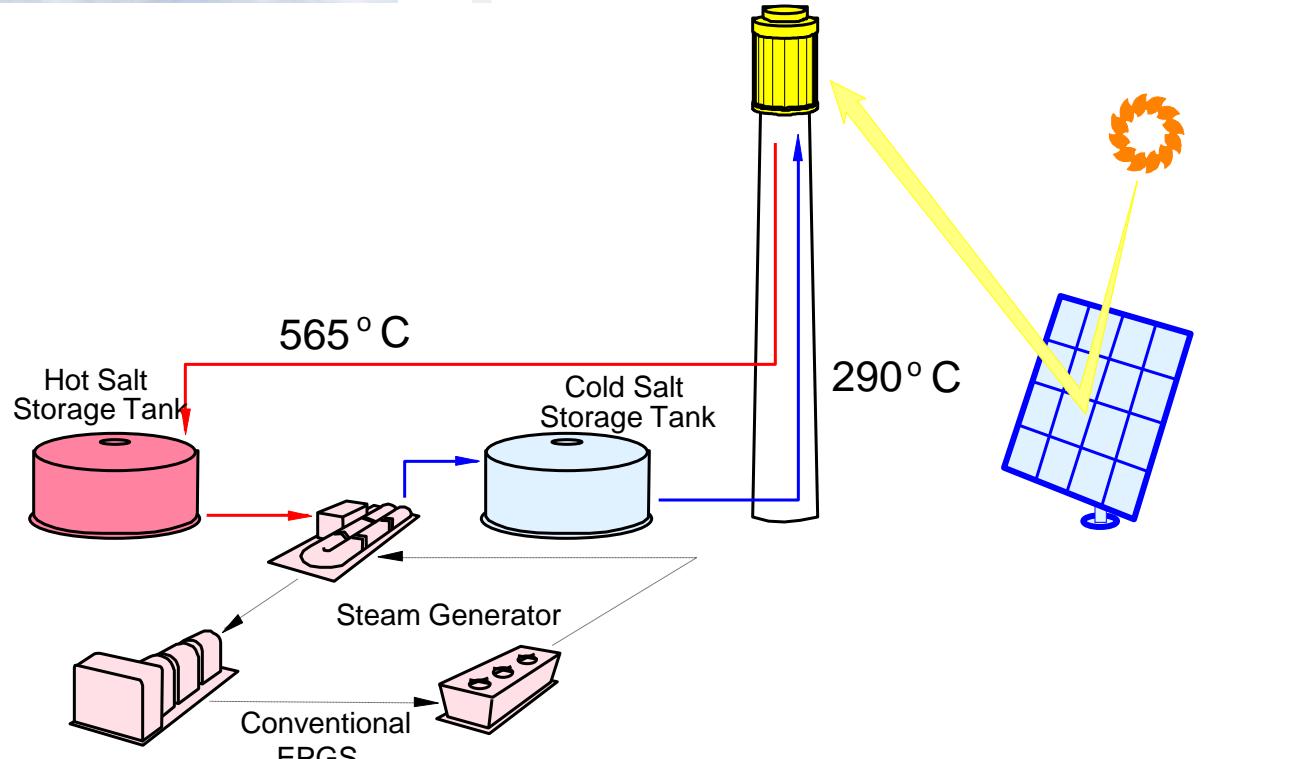


## Crescent Dunes Solar Energy Project

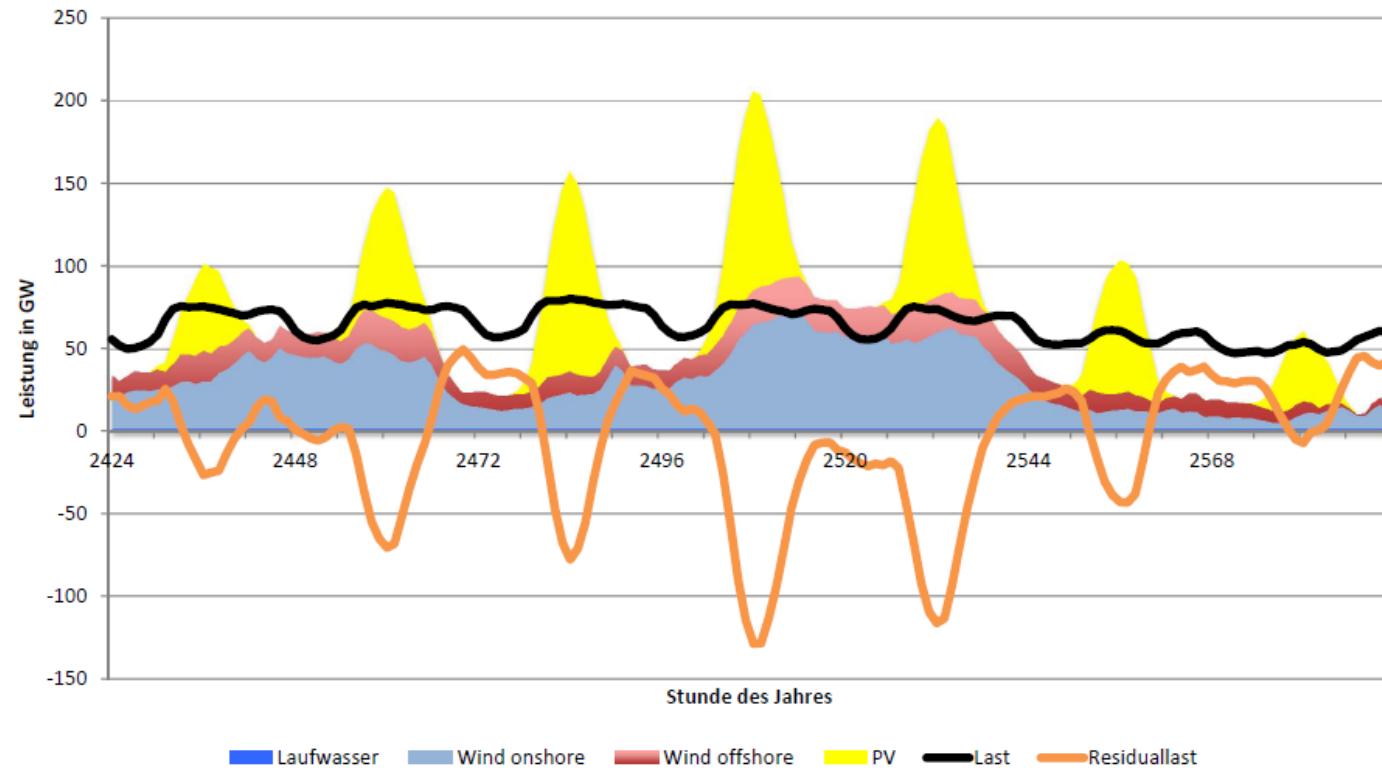
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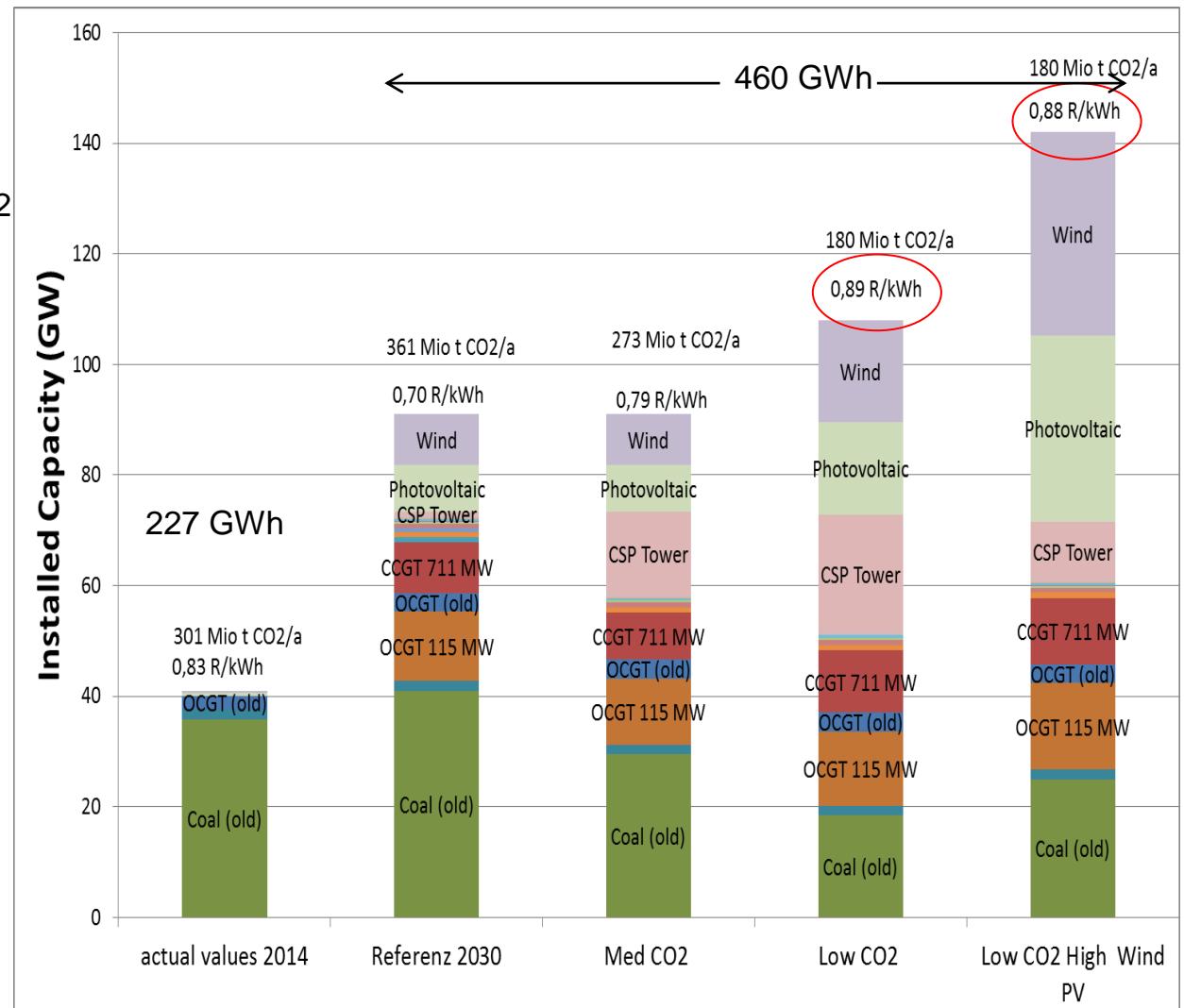


## What is Residual Load and which technologies can cover them best at high fractions of fluctuation renewables?



## Example: Cost-optimized energy mix for South Africa in 2030

- Coal and gas are the lowest cost options to cover the residual load
- CSP replaces fossil fuels if CO<sub>2</sub> emission reduction is required
- The optimum mix of CSP, PV and wind strongly depends on the cost structure of all three technologies

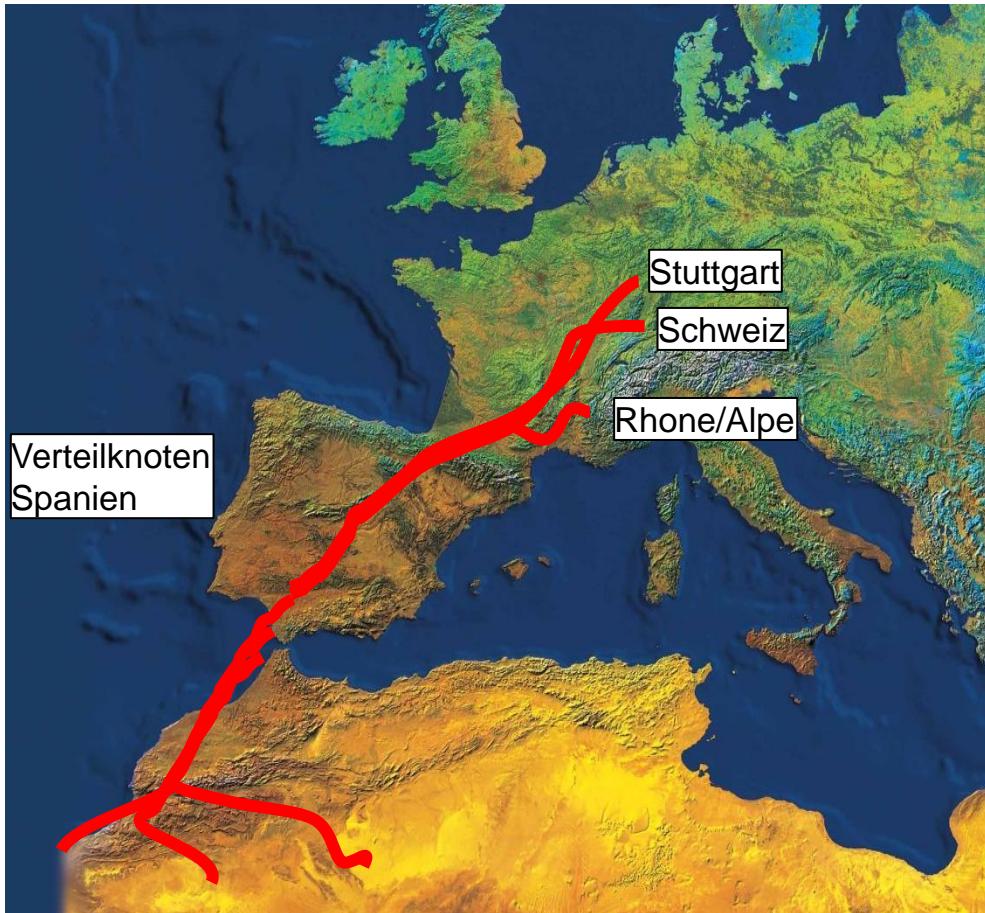


## Economics – German Energy System with and without import of solar electricity

- The electricity supply shall be provided at lowest cost
- Two scenarios are compared
  - One, where Germany is supplied only by in-country solar and wind energy generators
  - The other, where import of dispatchable electricity import is complementing in-country renewables



## Solar electricity import



- **Phase I**

Transport of solar electricity from southern Europe to Europe's load centers

- **Phase II**

Import of all year-round dispatchable electricity from North Africa

# Germany 20XX:

- 90% RE scenario /wo dispatchable electricity import
- 375 GW + 40 GW Grid + 40 GW electric storage

Energieträger	Installierte Leistung	Pro Jahr gelieferte Strommenge	Mittlere Auslastung
	MW	TWh/a	h/a
<b>Fluktuierend / Erneuerbar</b>	235500	551.3	
Photovoltaik	100000	98.9	989
Wind Onshore	70000	156.4	2235
Wind Offshore	60000	257.7	4295
Laufwasserkraft	5500	38.2	6951
<b>Regelbar / Erneuerbar</b>	8000	37.9	
Biomasseabfälle, Müll	4000	22.1	5515
Holz, Energiepflanzen, Biogas	4000	15.9	3964
Geothermie		0.0	0
Import Wasserkraft per HGÜ		0.0	0
Import Solarstrom per HGÜ		0.0	0
<b>Fossil / Nuklear</b>	90000	56.4	
Gasturbinenkraftwerke	90000	56.4	627
Kohlekraftwerke	0	0.0	0
GuD und BHKW	0	0.0	0
Kernkraftwerke	0	0.0	0
Braunkohlekraftwerke	0	0.0	0
<b>Speicher und Netztransfer</b>	80000	48.7	
Pump-und Druckluftspeicher	20000	15.7	785
H2-Speicher Leistung	20000	13.8	688
H2-Speicher Kapazität (Tage)	1		
Netztransferekapazität (NTC)	40000	19.3	482
<b>Gesamter Kraftwerkspark</b>	373500	579	1551

- 90% RE scenario /w dispatchable electricity import
- 225 GW + 8 GW grid + 20 GW HVDC + 8 GW electric storage

Energieträger	Installierte Leistung	Pro Jahr gelieferte Strommenge	Mittlere Auslastung
	MW	TWh/a	h/a
<b>Fluktuierend / Erneuerbar</b>	117500	288.1	
Photovoltaik	45000	44.5	989
Wind Onshore	40000	89.4	2235
Wind Offshore	27000	116.0	4295
Laufwasserkraft	5500	38.2	6951
<b>Regelbar / Erneuerbar</b>	35000	220.2	
Biomasseabfälle, Müll	4000	30.0	7502
Holz, Energiepflanzen, Biogas	7000	49.8	7112
Geothermie	4000	30.2	7547
Import Wasserkraft per HGÜ	4000	25.8	6462
Import Solarstrom per HGÜ	16000	84.3	5271
<b>Fossil / Nuklear</b>	65000	54.4	
Gasturbinenkraftwerke	65000	54.4	837
Kohlekraftwerke	0	0.0	0
GuD und BHKW	0	0.0	0
Kernkraftwerke	0	0.0	0
Braunkohlekraftwerke	0	0.0	0
<b>Speicher und Netztransfer</b>	16000	3.1	
Pump-und Druckluftspeicher	7500	1.9	255
H2-Speicher Leistung	0	0.0	0
H2-Speicher Kapazität (Tage)	0		
Netztransferekapazität (NTC)	8500	1.1	135
<b>Gesamter Kraftwerkspark</b>	225000	561	2494

## Dispatchable electricity imports

up to 5 times less grid capacity

up to 5 times less storage capacity

up to 150 GW less power plant capacity



# Summary of CSP Characteristics

- Concentrates direct radiation to generate high temperature heat
- Heat can be stored at low cost using molten salt as fluid
- Installation in Large Centralized Units
- Trough, Tower and Fresnel Technologies
- CSP with thermal storage complements fluctuating renewables like wind and PV

