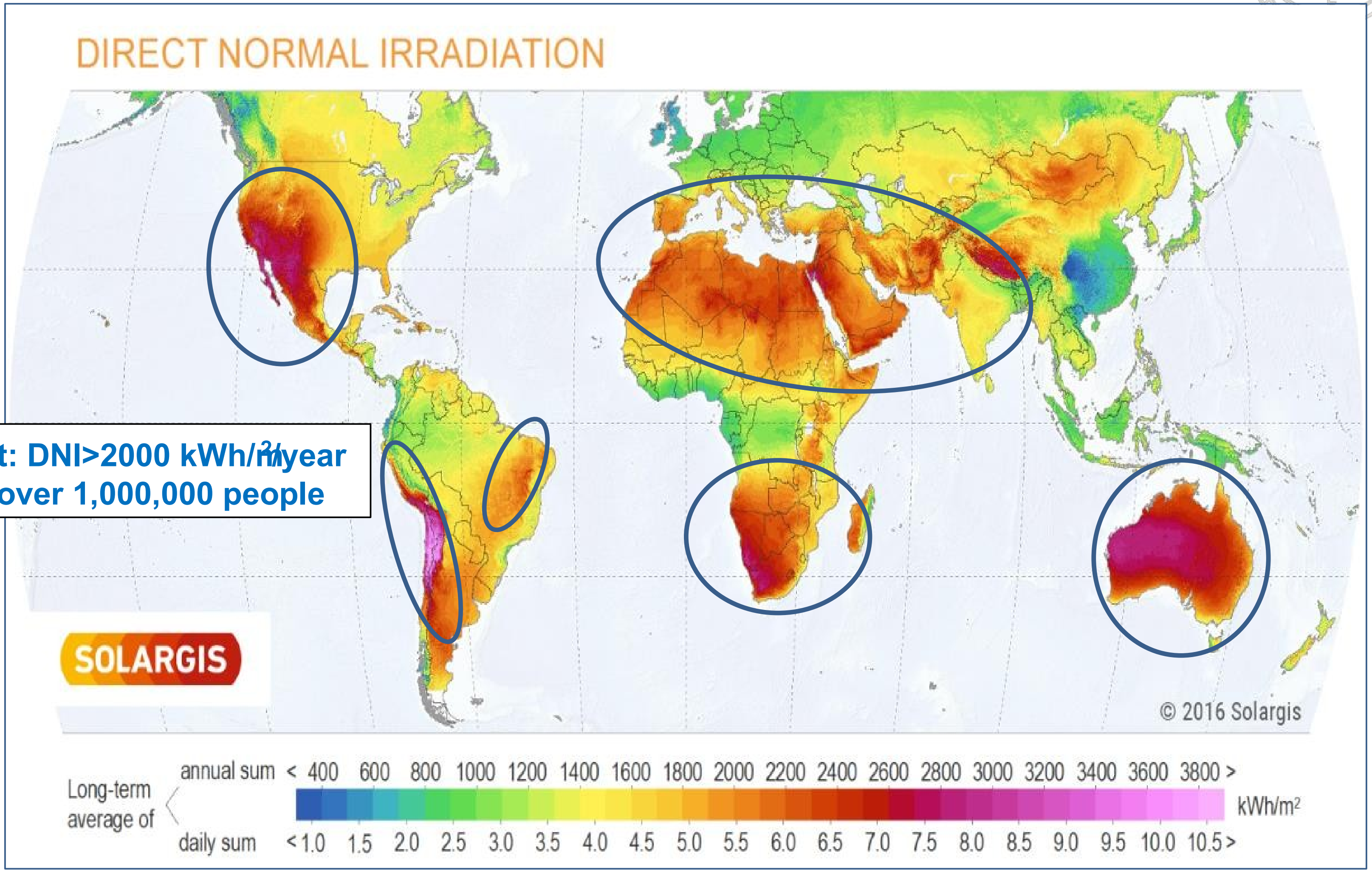
PC 8
Solar Energy

PHY 555 – Energy & Environment

Erik Johnson, Mathieu de Naurois, Daniel Suchet

Solar Resource



The sunbelt: DNI>2000 kWh/m²/year
70 cities over 1,000,000 people

A. Ferriere, CNRS/PROMES

The 2 ways

Diagram 1. The photovoltaic effect

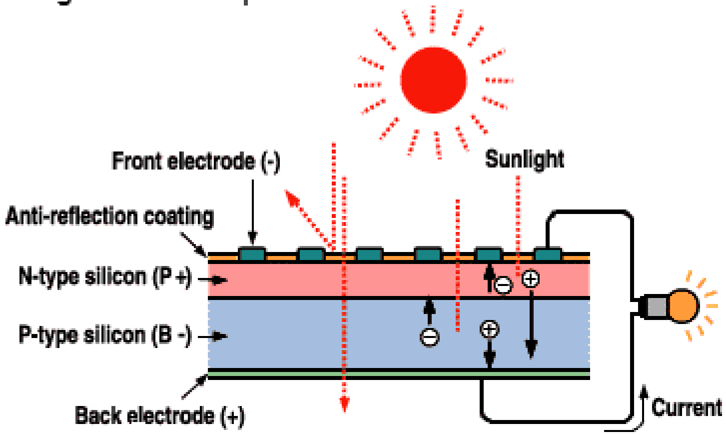
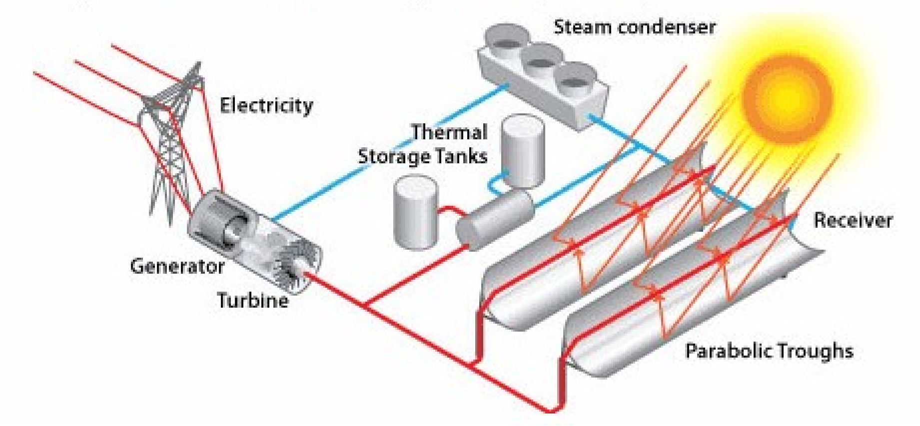
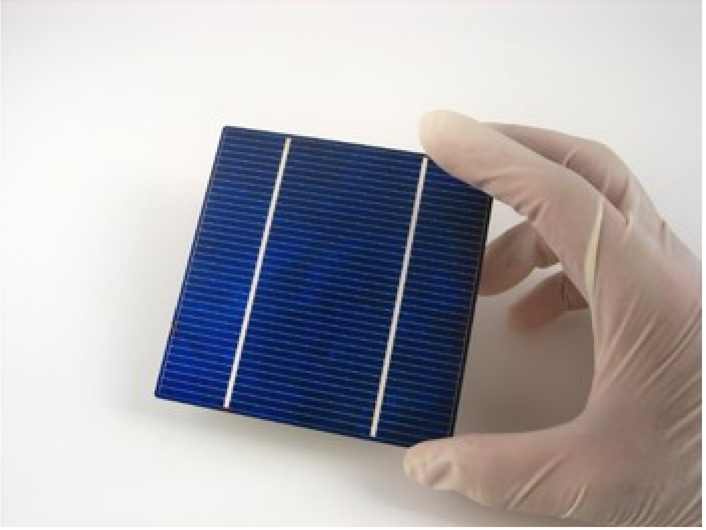


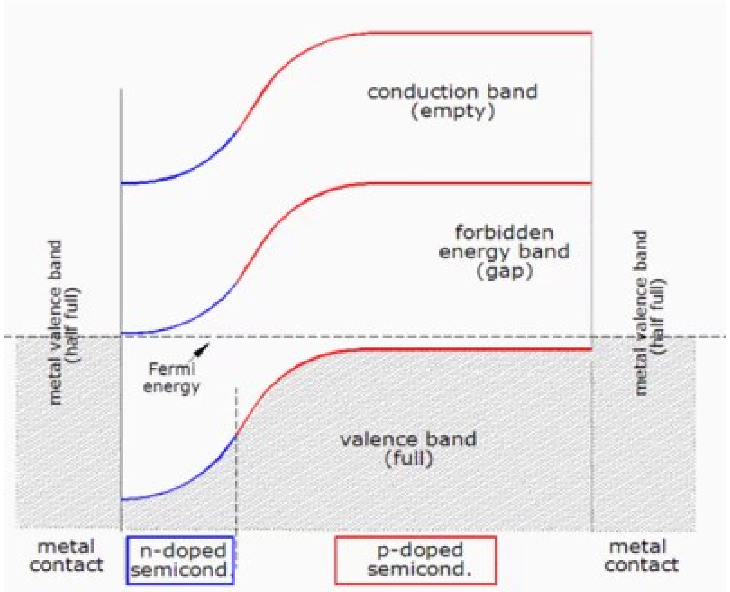
Diagram 2. Parabolic trough solar power plant

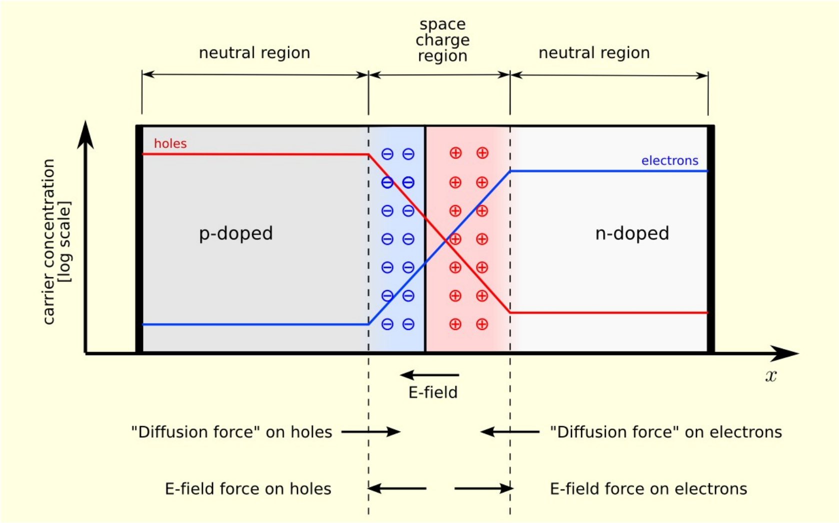


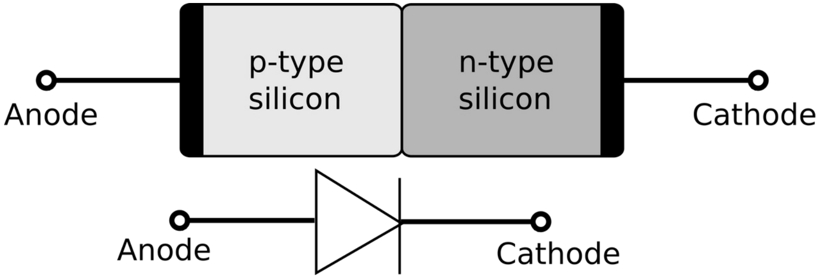


Photovoltaic Cells

- Dopped np semiconductor (current can only flow in one direction)
  - Photons in sunlight hit the solar panel and are absorbed
  - Generates an electron-hole pair
  - Electron drifts towards the n junction, hole towards the p junction

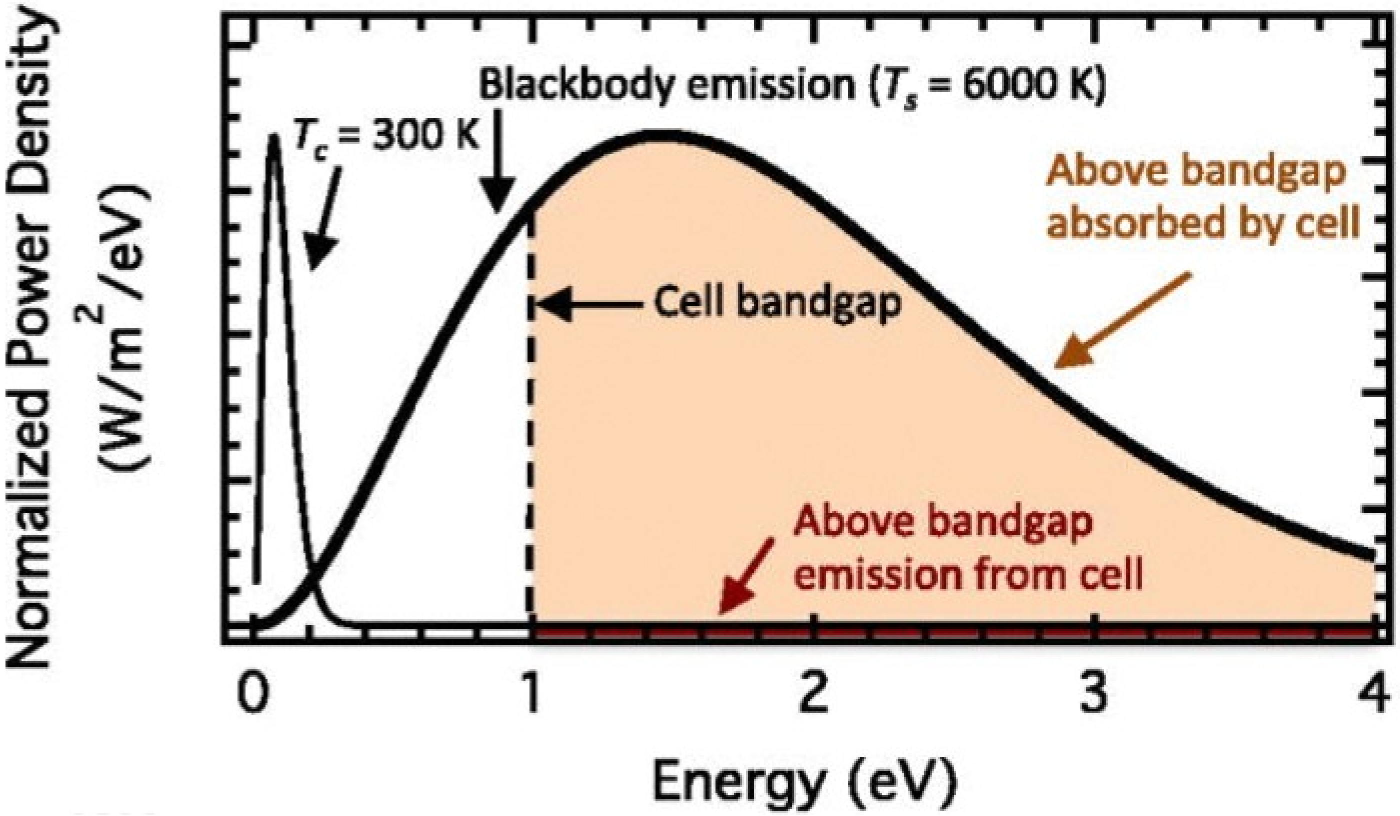




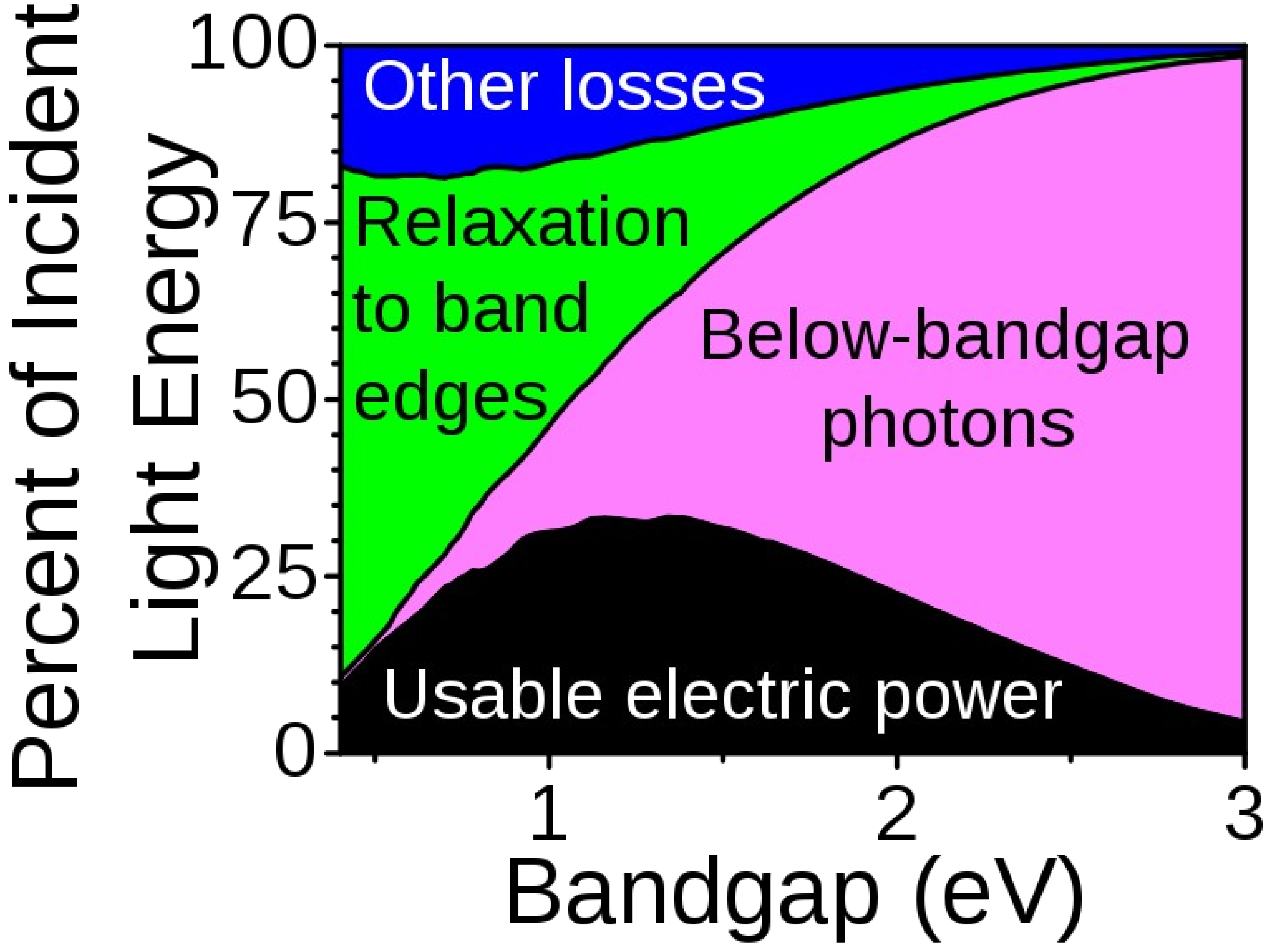


Shockley–Queisser limit

- Photons with energy greater than the bandgap are absorbed, the others are lots
- Only the bandgap energy is recovered.
- Leads to a maximum recoverable power, depending on input spectrum

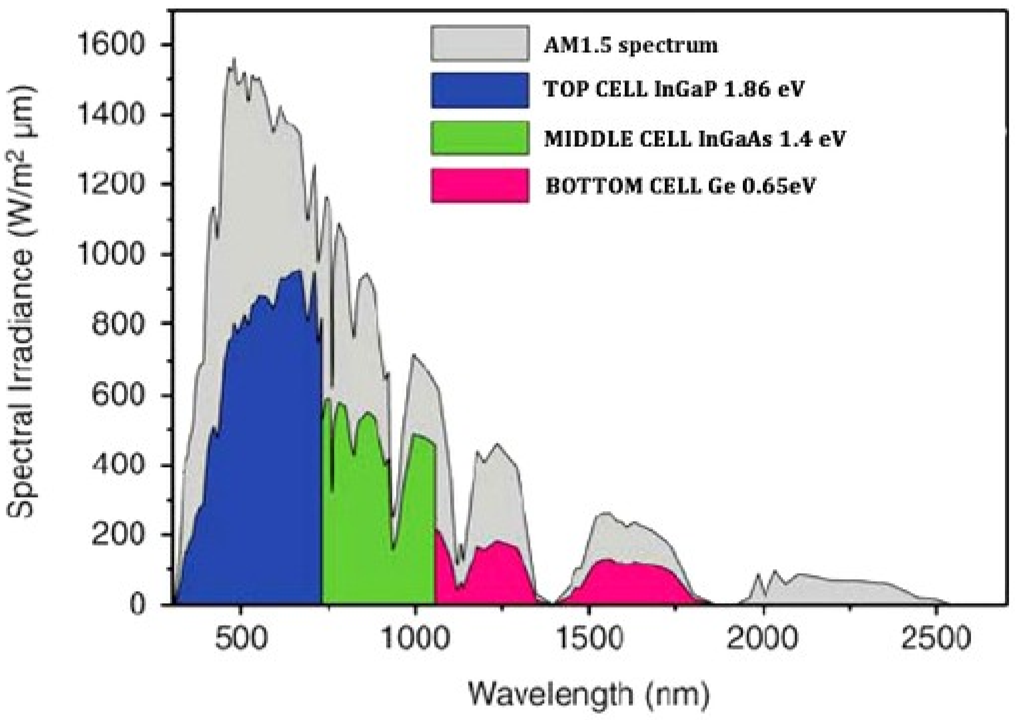


Shockley–Queisser limit – Losses

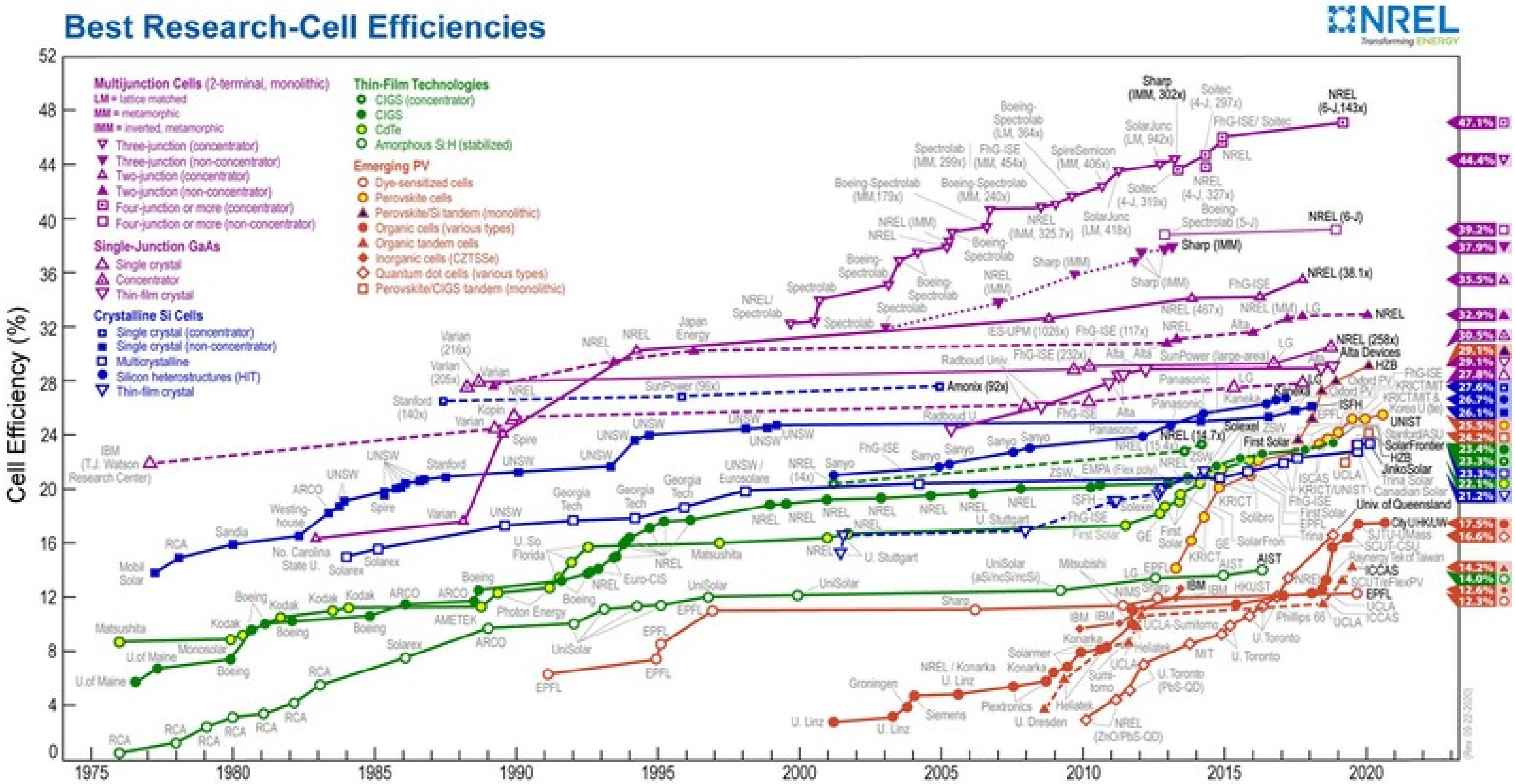


Beating the Shockley–Queisser limit

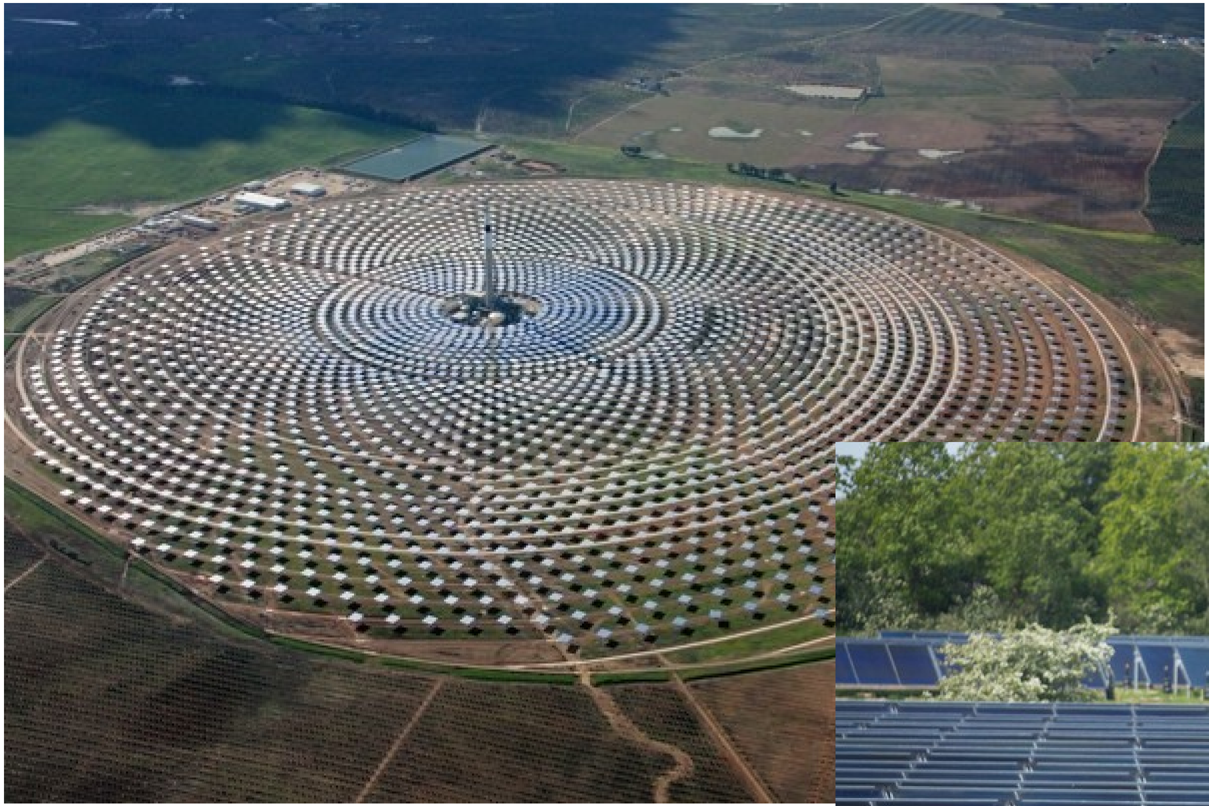
- Multiple approaches:
  - Multifunction cells: stack of cells with different gaps
  - Light concentration
  - Intermediate band level: energy band between valence & condition bands ⇒ absorption of 2 photons
  - Photon upconversion: absorp of several below-bandgap phc followed by emission of one above-bandgap photon
  - Use of Fluorescence downconversion/downshifting
  - ...



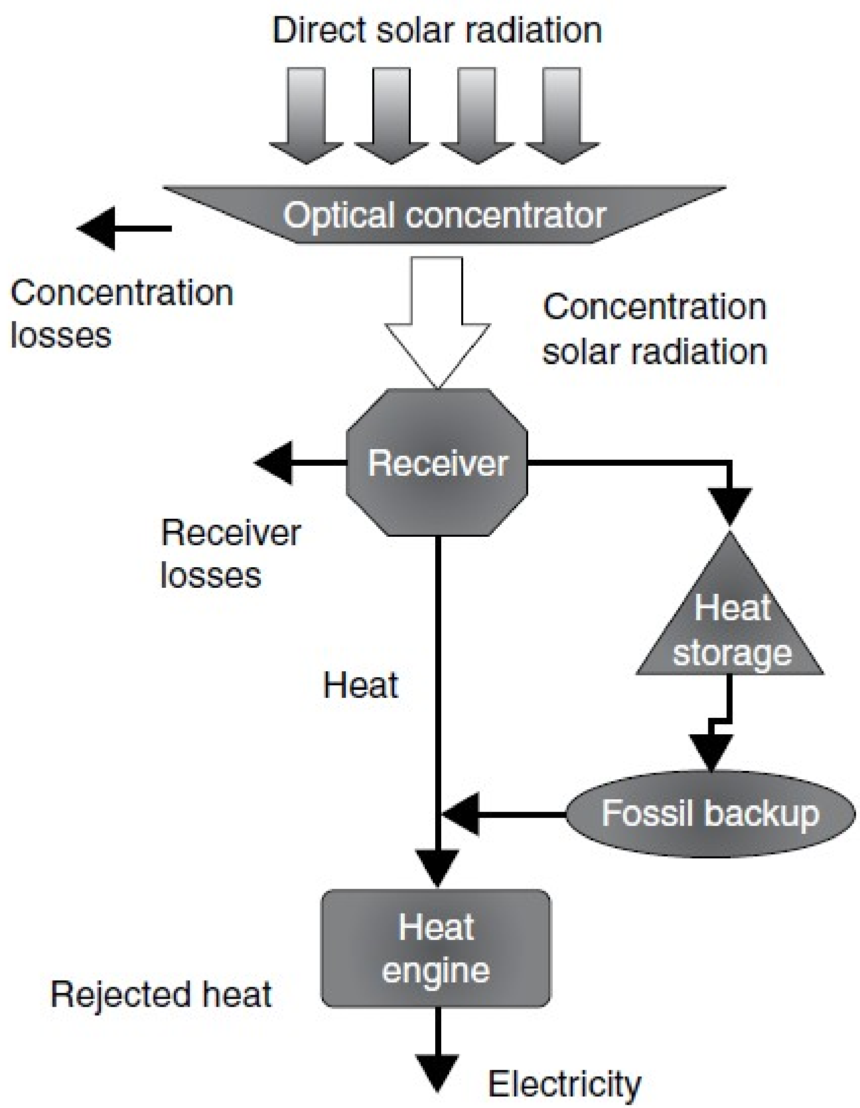
Current Cell Efficiency

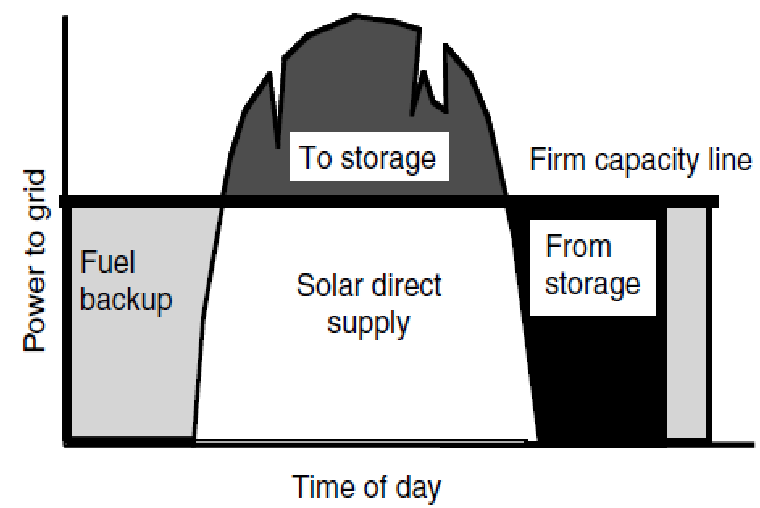


Thermal Solar

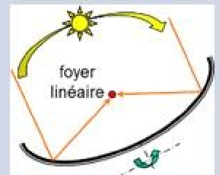
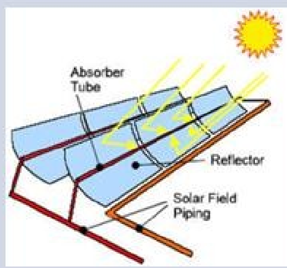
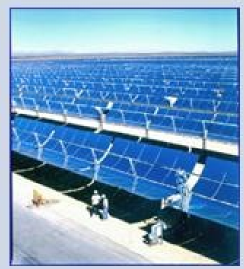
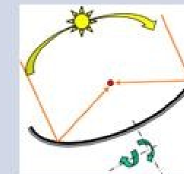
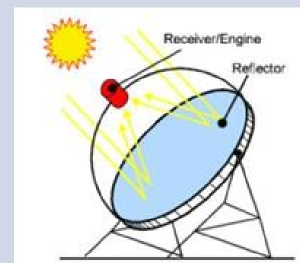
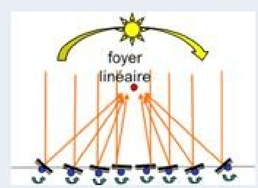
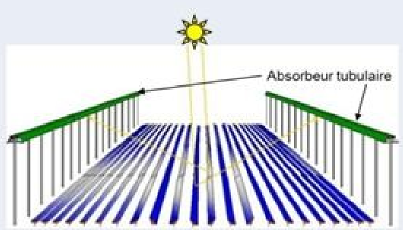
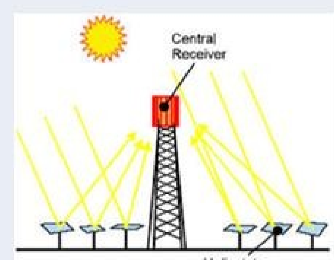


Solar energy with concentration: Schematic diagram





Technologies

	Linear concentration (2D)	Point focus (3D)
Moving focus	**Parabolic Trough collectors** Mobile reflector (1 axis) Linear receiver Modular design Peak concentration 100   	**Parabolic Dish collector** Mobile reflector (2 axis) Central receiver Peak concentration 10.000   
Fixed Focus	**Linear Fresnel Reflector Collectors (CLFR)** Mobile reflector (1 axis) Linear receiver Modular design Peak concentration 100   	**Tower systems** Heliostat Field (2 axis) Fix-focus central receiver Peak concentration 1000   

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Various concentration systems

Diagram 2. Parabolic trough solar power plant

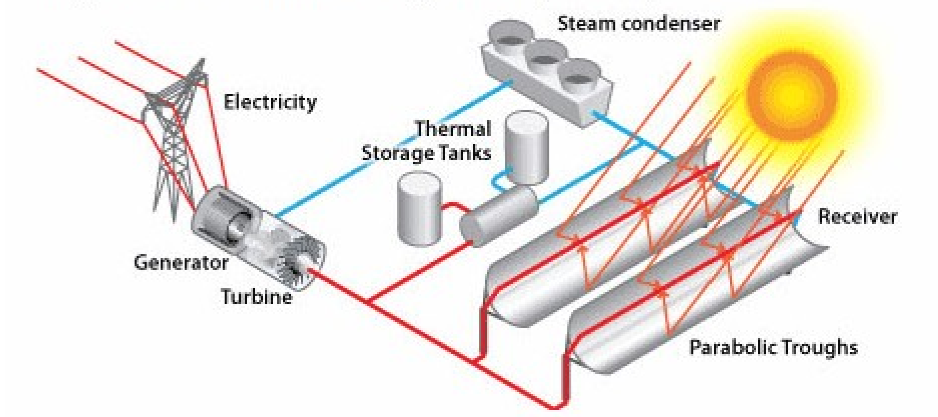


Diagram 3. Solar power tower plant

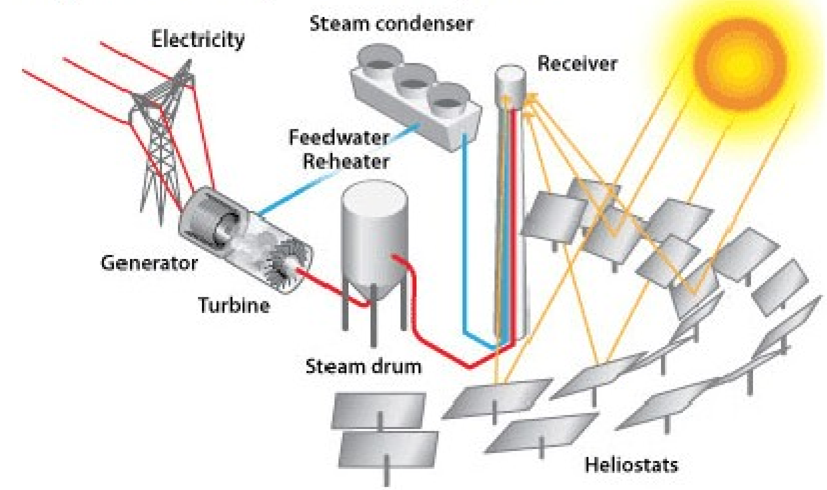


Diagram 4. Solar dish power plant

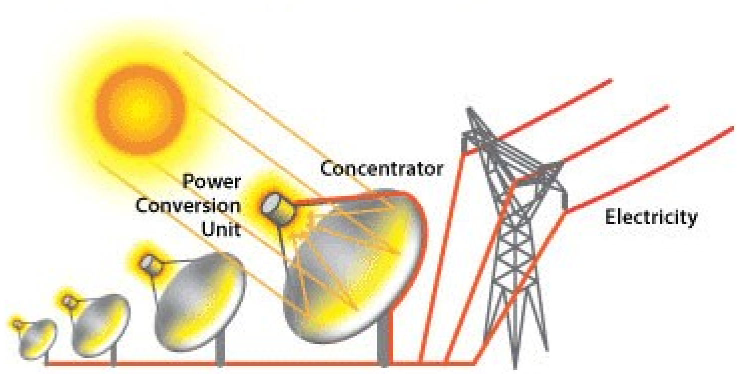
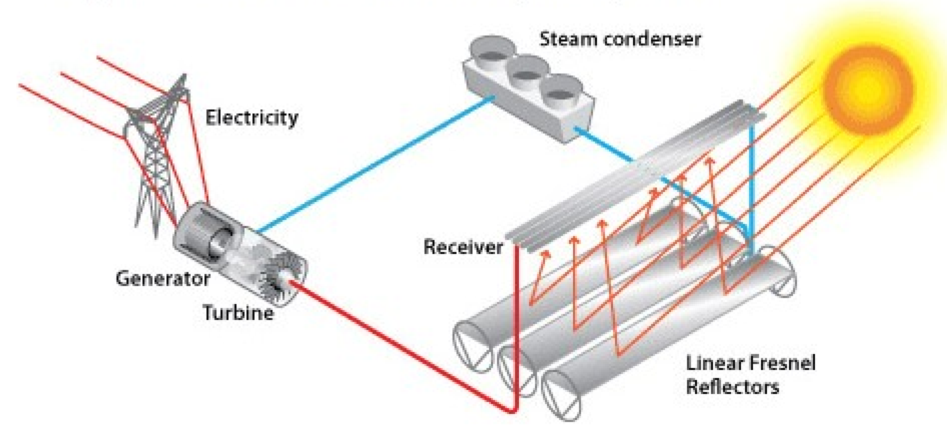


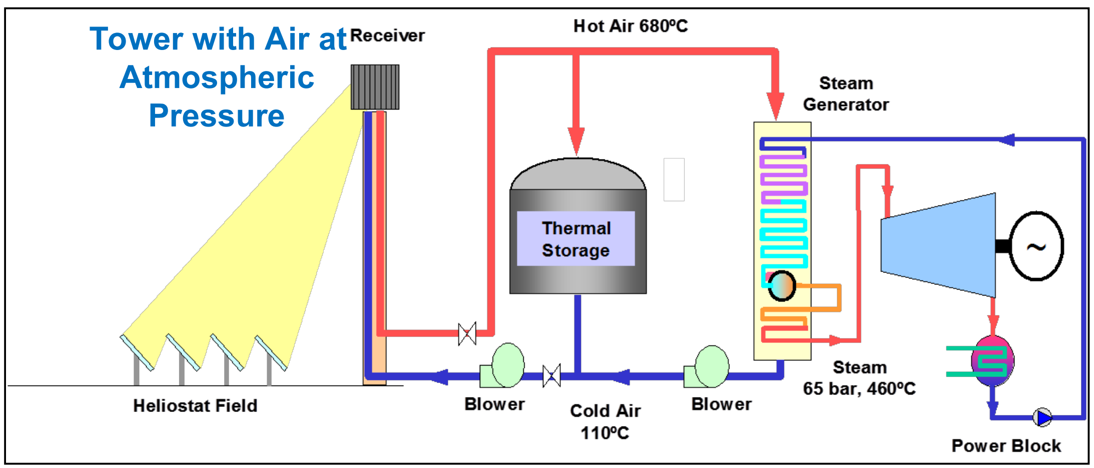
Diagram 5. Linear Fresnel solar power plant

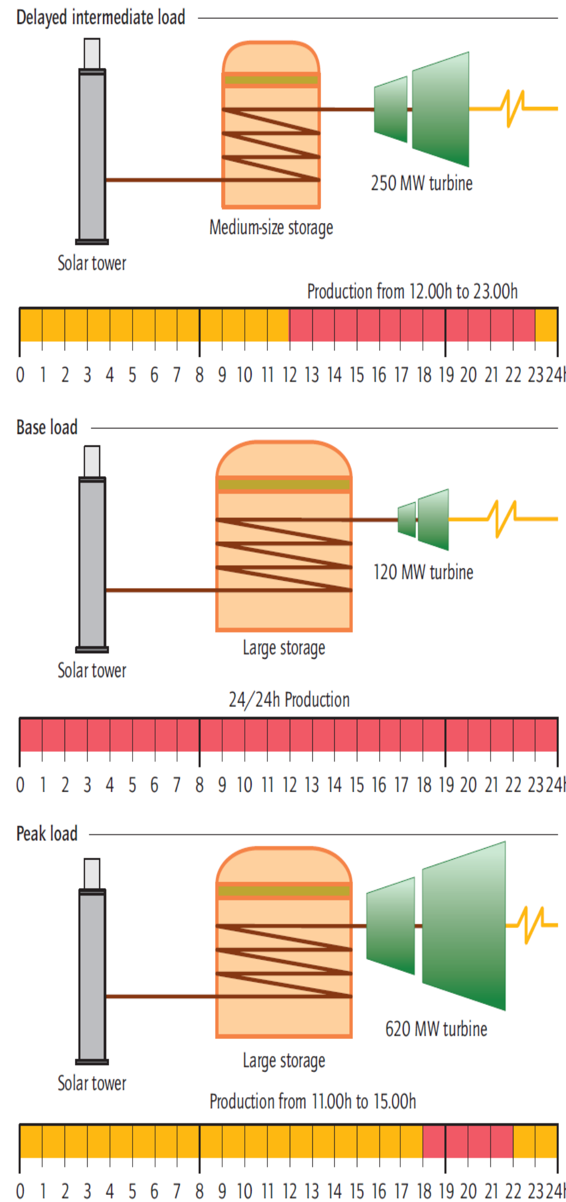


https://www.bls.gov/green/solar_power/

HEAT Storage

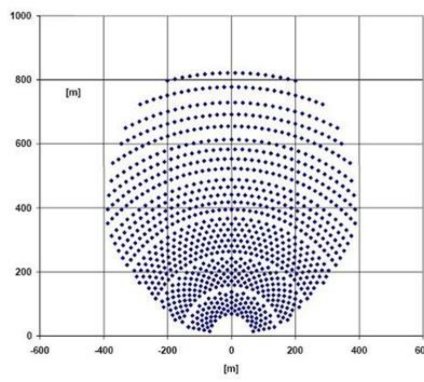
- 3 usages:
  - Shifting power generation
  - Cover base load
  - Satisfy Peak Load



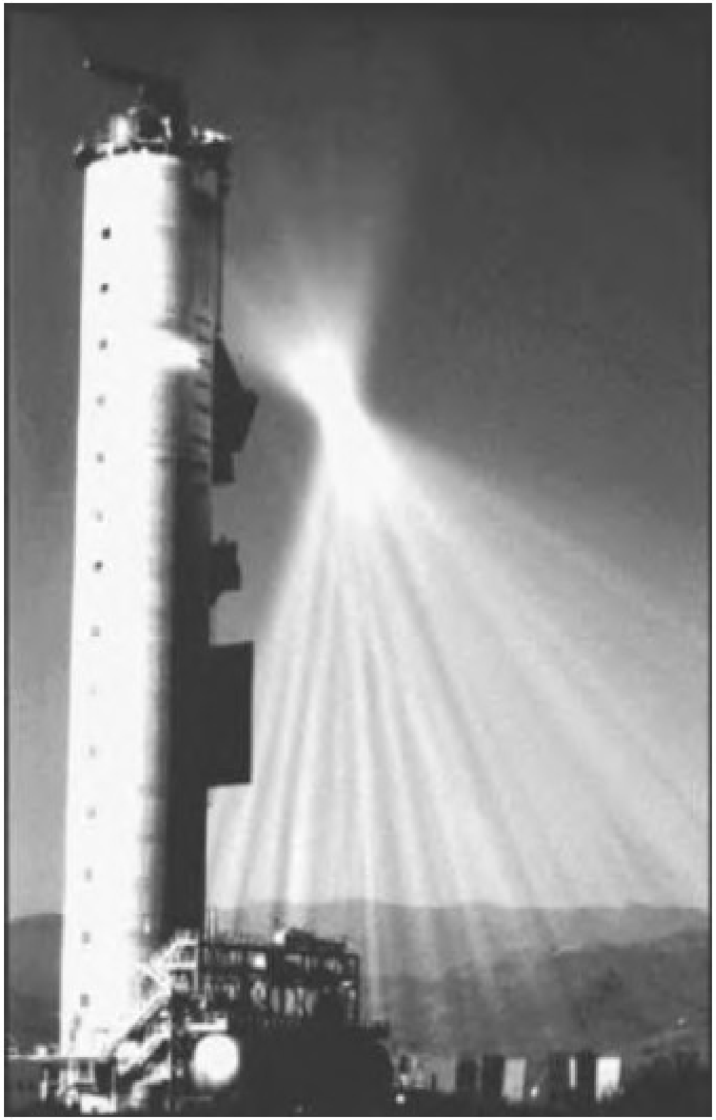


PS10 and PS20 (Spain) : 10 + 20 MW

PS20 (Spain)
20 MW$_e$, steam Rankine cycle
Technology : tower with direct saturated steam generation (250°C, 40 bar)
Solar field: 150.600 m² (1255 heliostats of 120 m²)
Storage 30' - Hybridization with NG (12 to 15%)



Solar Tower



Convergence before focusing on the tower

Andasol (Spain) : 3 x 50MWe

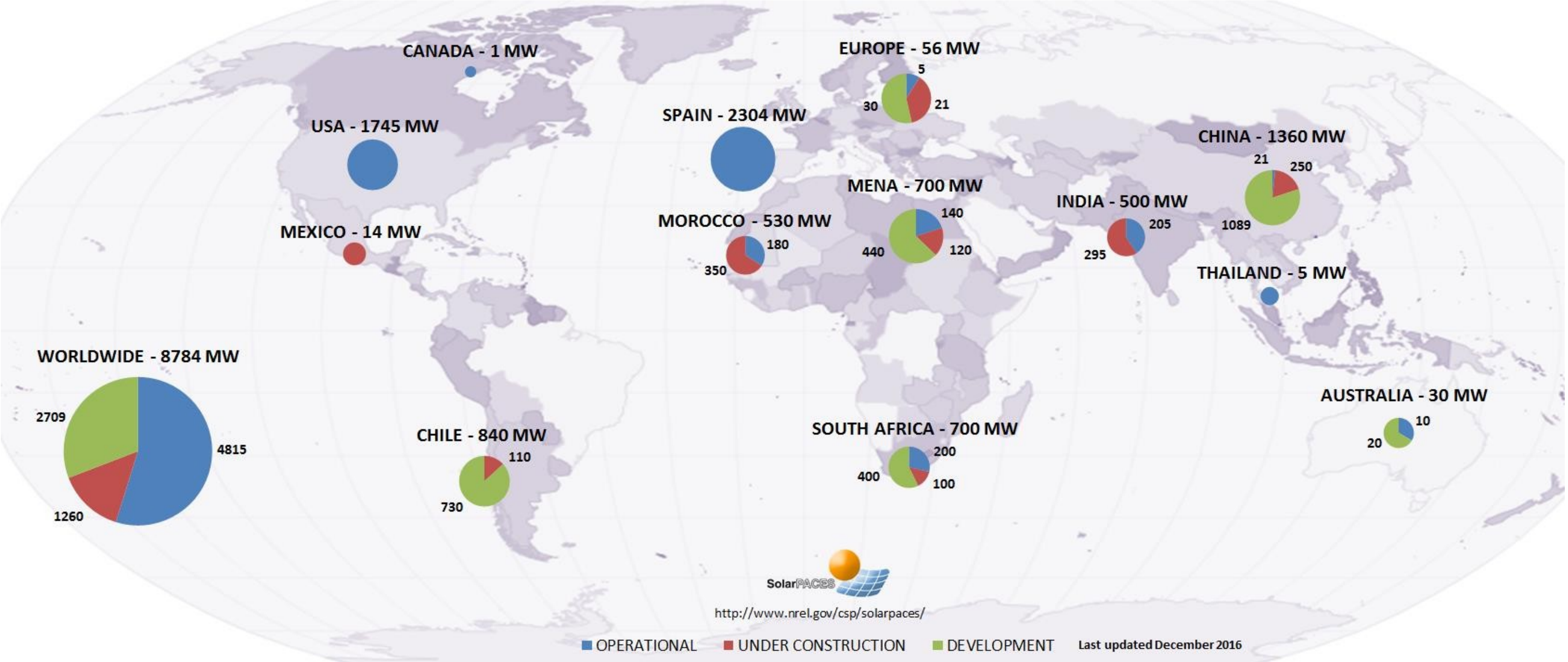
- star of operation: 2009-2011, 2200 kWh/m^2 per year
- 3×51 ha of collectors, ~200 000 parabolic mirror
- 3×180 GWh per year (3x20 MW)
- heat storage in melted salt: 7.5 h, 1 GWh(th) per storage
- Spain: 1,5 GWe installed ~ 2% of electricity production

Linear Fresnel

- Puerto Errado 2 (Spain, 2012): 20 MW
- Liddell Power Station (Australia, 2012): 90 MW

Current installations

- Installed capacity in operation (2017): 4815 MW
- In construction: 1260 MW



Perspectives

Year	Installed capacity GW	Produced energy TWh	IEA scenario
2012	**1,4**	**4,2**	**-**
2017	11	33	Medium term market report
2035	246	845	450 ppm
2050	1108	4125	HiRen
2060	6000	25000	Solar Energy Perspective

Source: AIE

Schematic Diagram

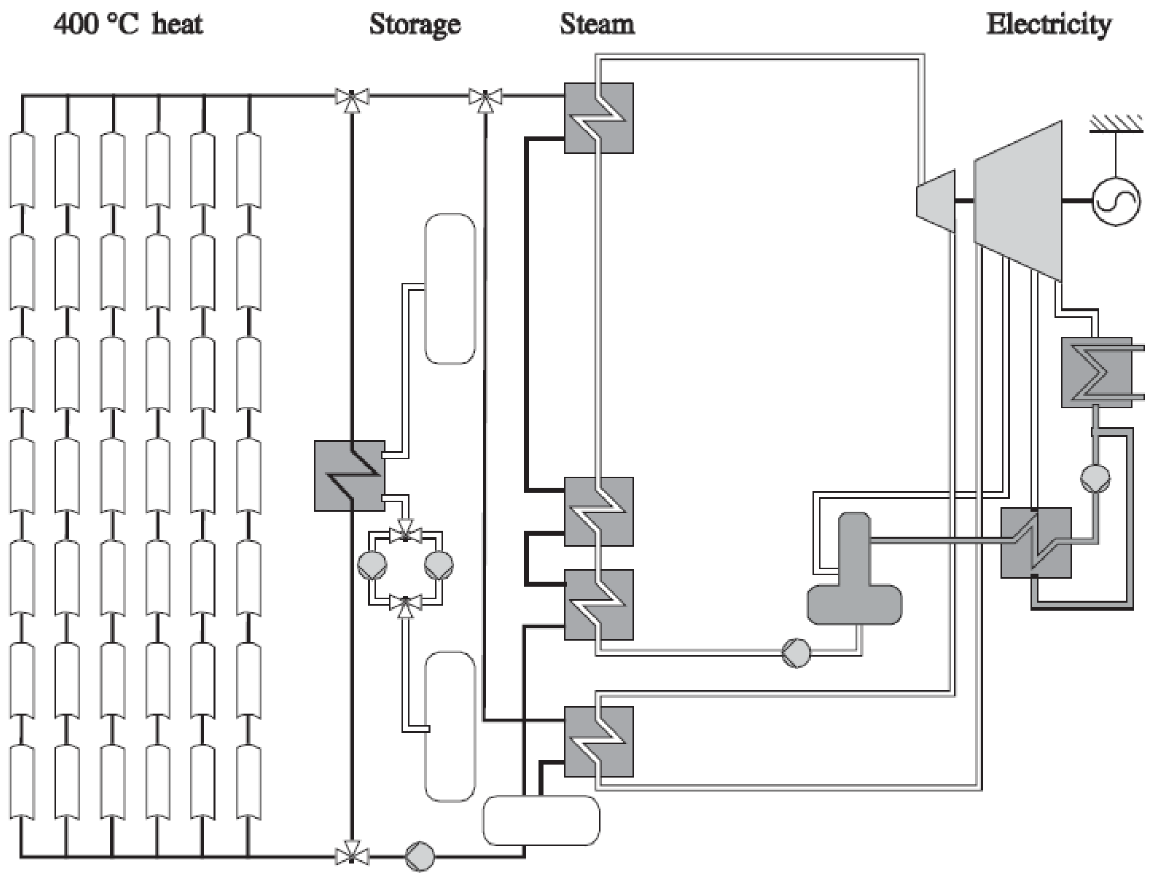
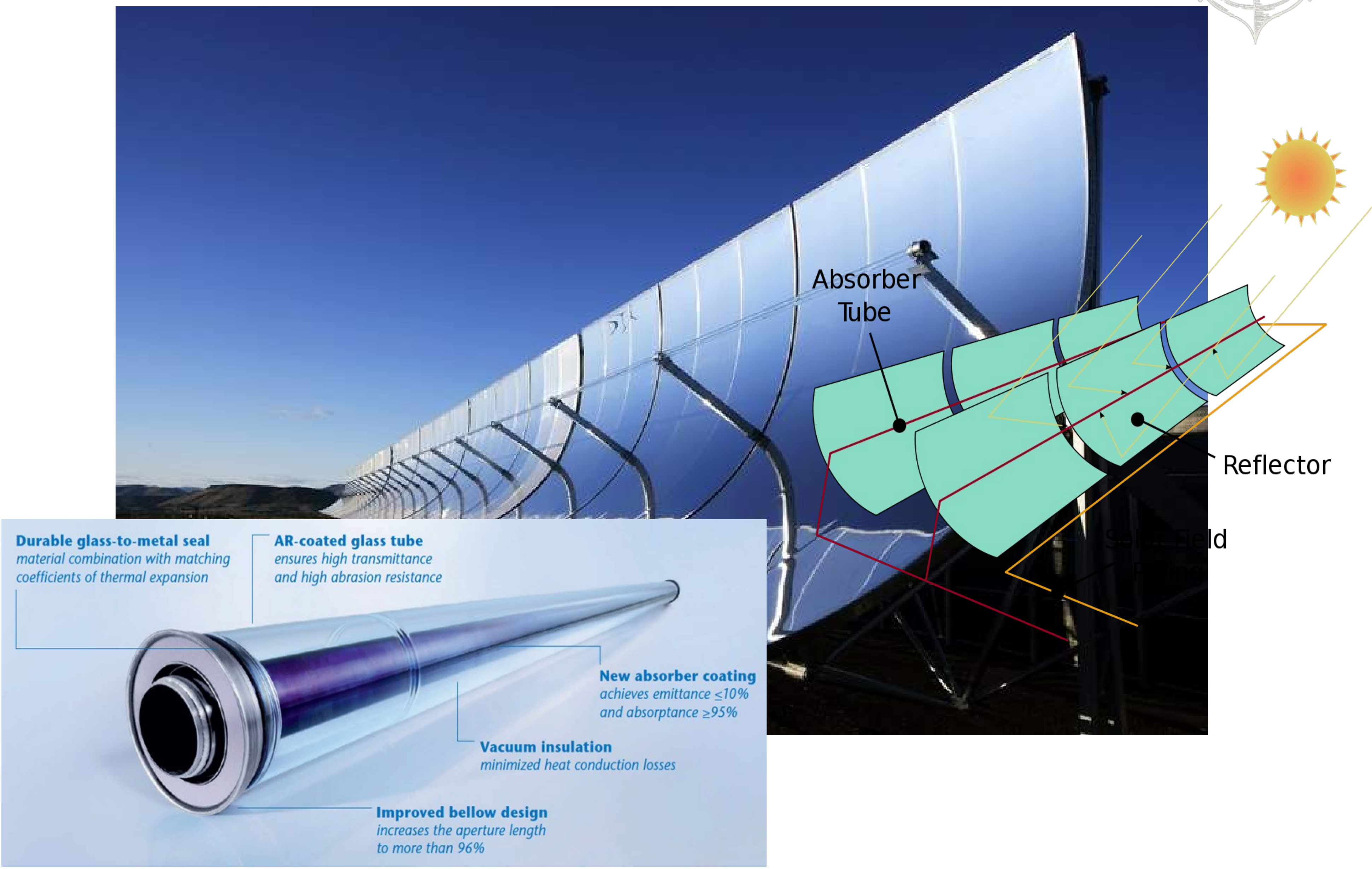


Figure 4.9. *The principle of a solar power station with cylindrical-parabolic collectors with oil (400°C) with storage in melted salt and Rankine cycle (source: Flabeg)*

Parabolic trough collectors (one-dimensional)



Tracking...

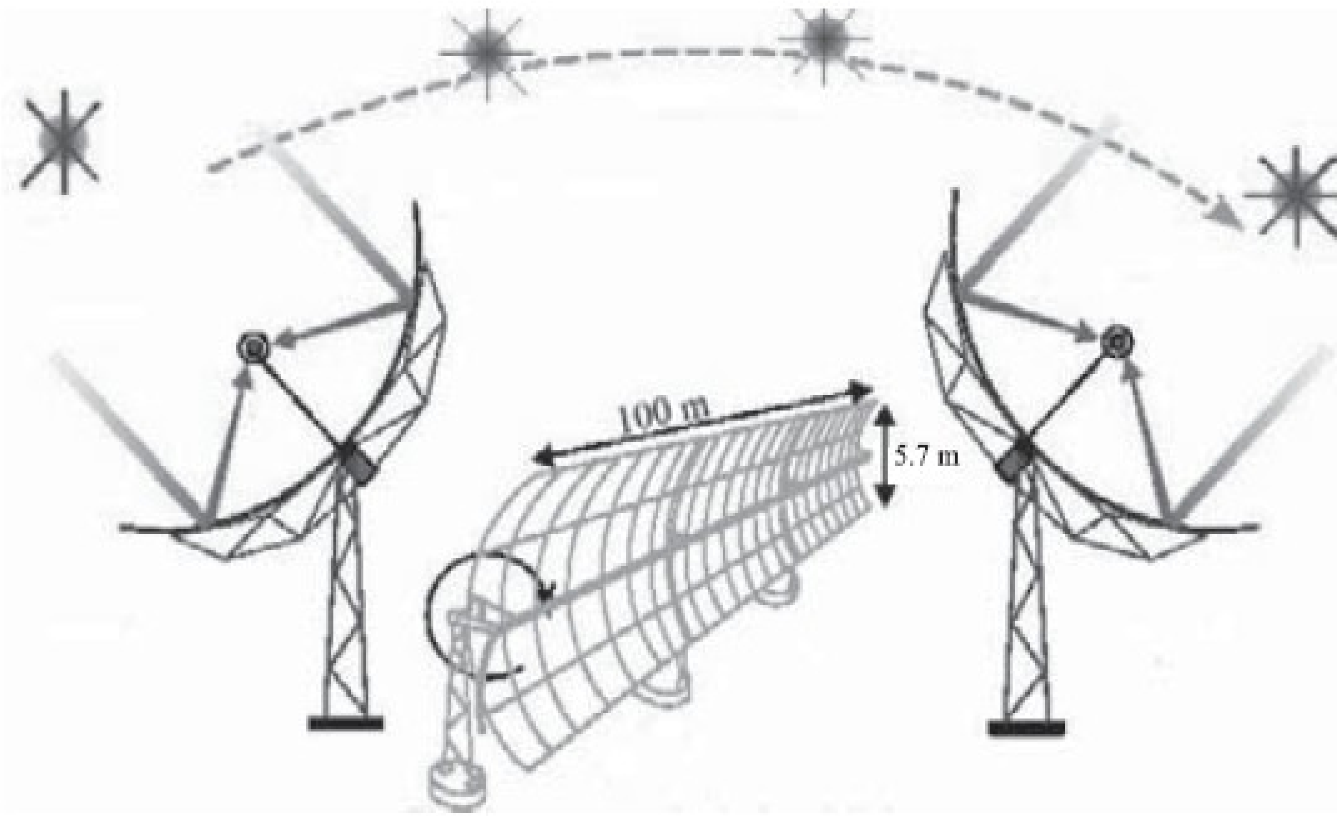
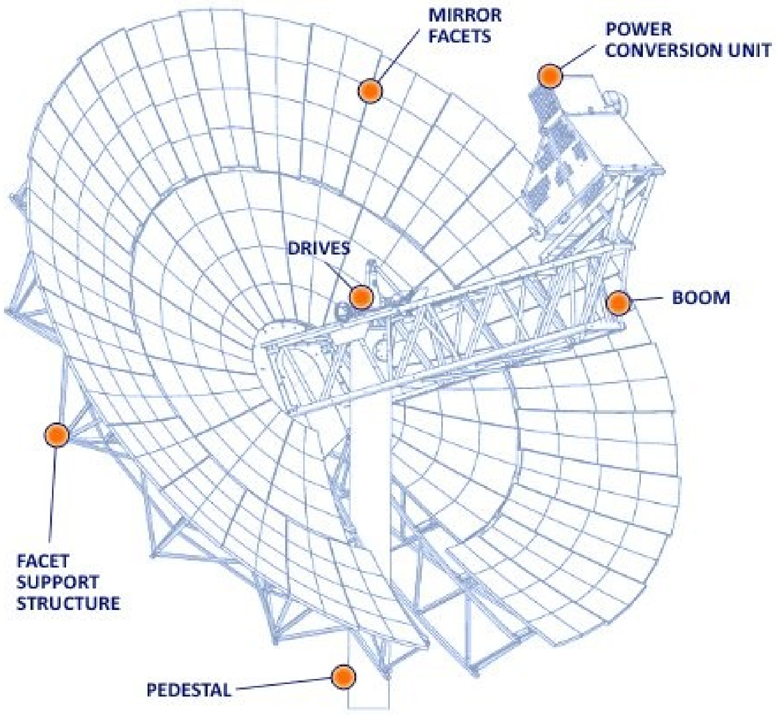


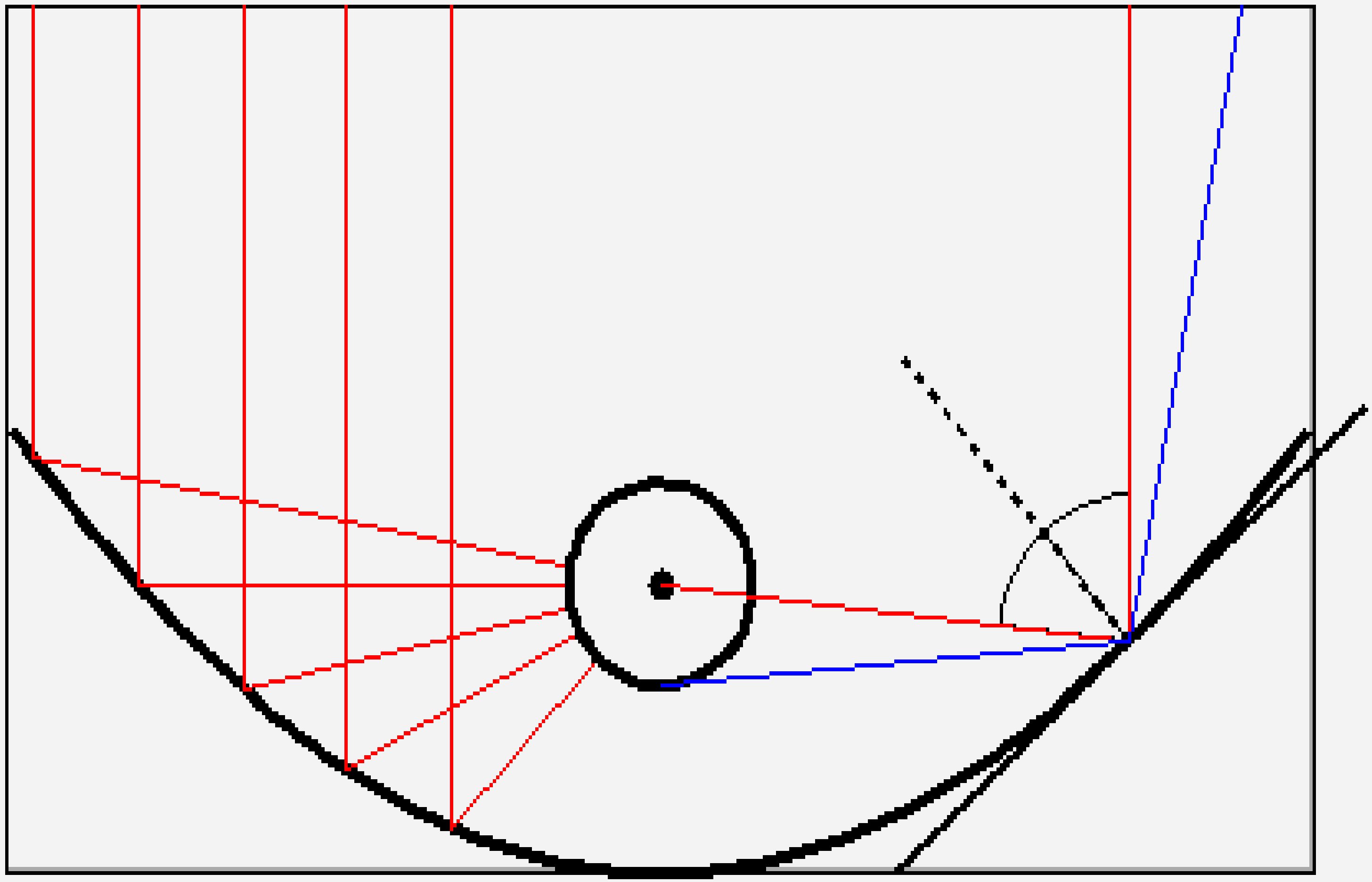
Figure 4.4. *Tracking the sun by a cylindrical-parabolic collector*

Two-dimensional manifolds "revolution dishes"

- Electricity production in isolated sites or farms
- Alt-azimuthal mount mandatory (pointing at the sun)
- Coupled to a Stirling engine (hence "dish / Stirling")

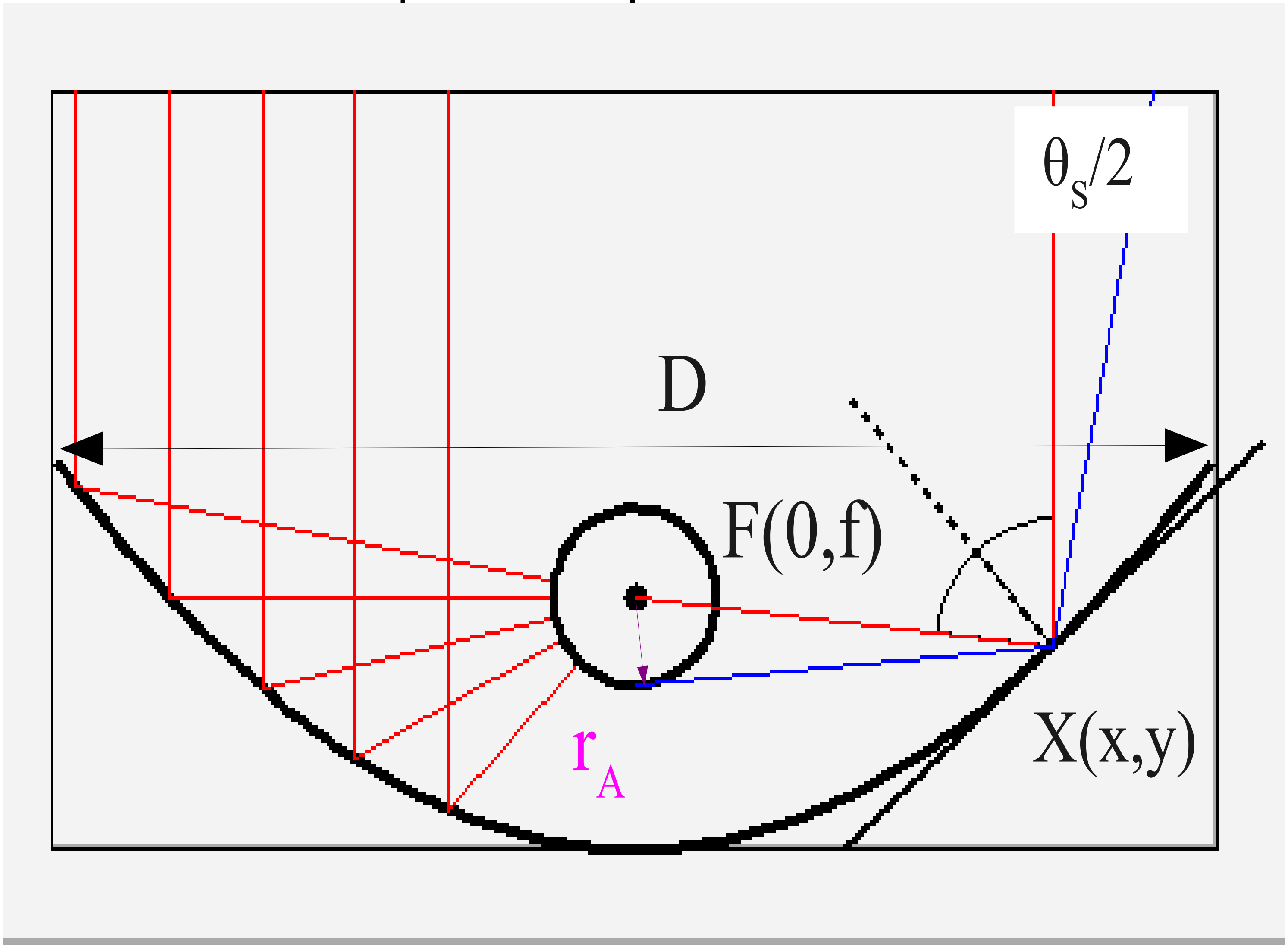


Size of collector



Parabolic collector: absorber diameter

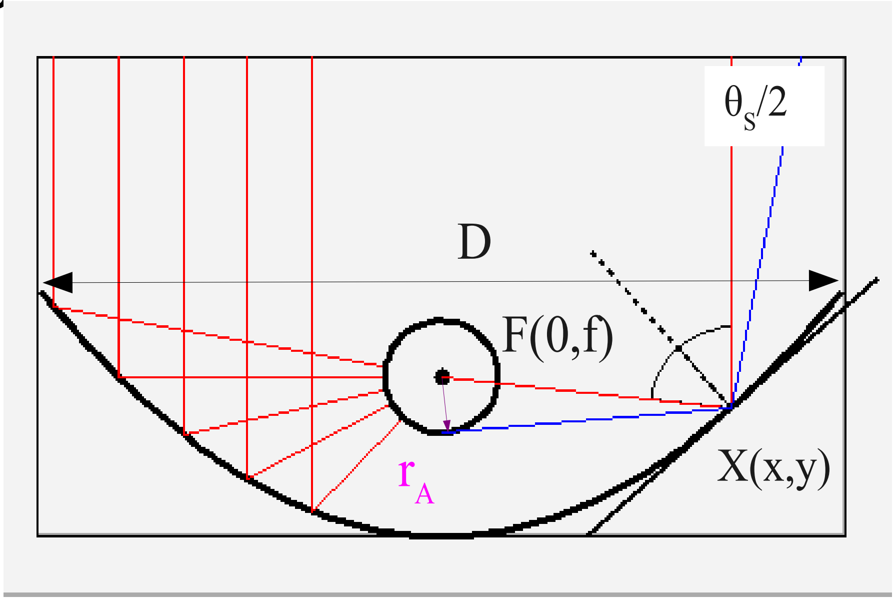
- The centre of the absorber tube is at the focus of the parabola
- The main axis of the parabola points to the sun's center



Collector Size

- the absorber tube is centered at the focus of the parabola
- for the marginal ray (from the edge of the sun) to reach the absorber, its radius should be larger than the distance from focus to the ray:

$$r_A > |FX| \sin(\theta_S/2)$$



$$|FX| = \sqrt{x^2 + (y-f)^2} = \sqrt{x^2 + \left(\frac{x^2}{4f} - f\right)^2} = f \times \left[\frac{1}{4}\left(\frac{x}{f}\right)^2 + 1\right]$$

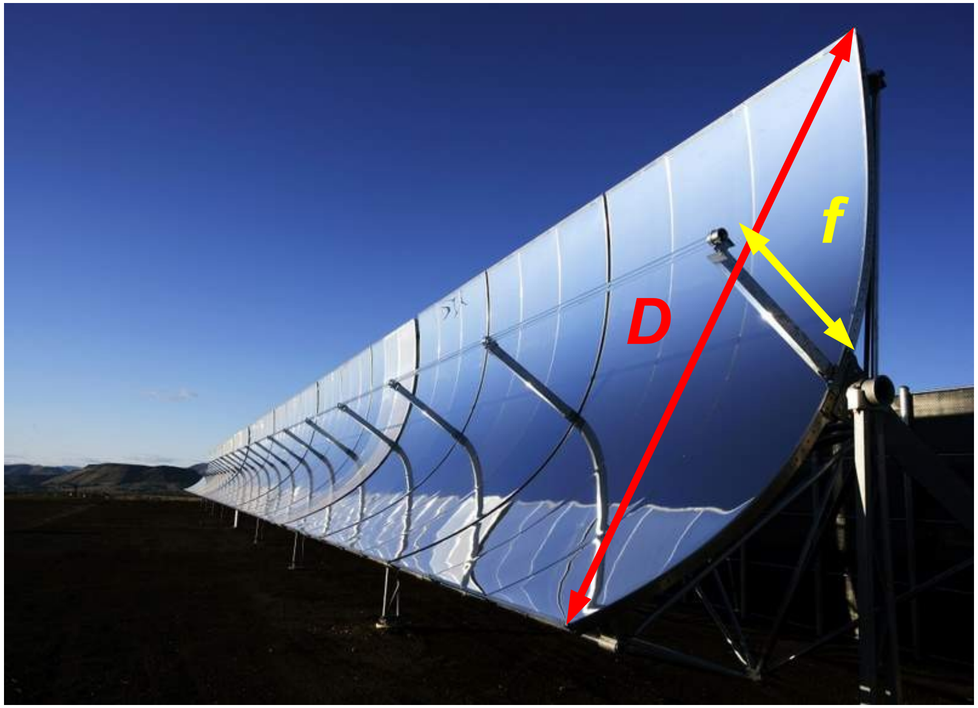
$$r_A > \sin(\theta_S/2) \times f \times \left(\frac{1}{4}\left(\frac{D}{2f}\right)^2 + 1\right)$$

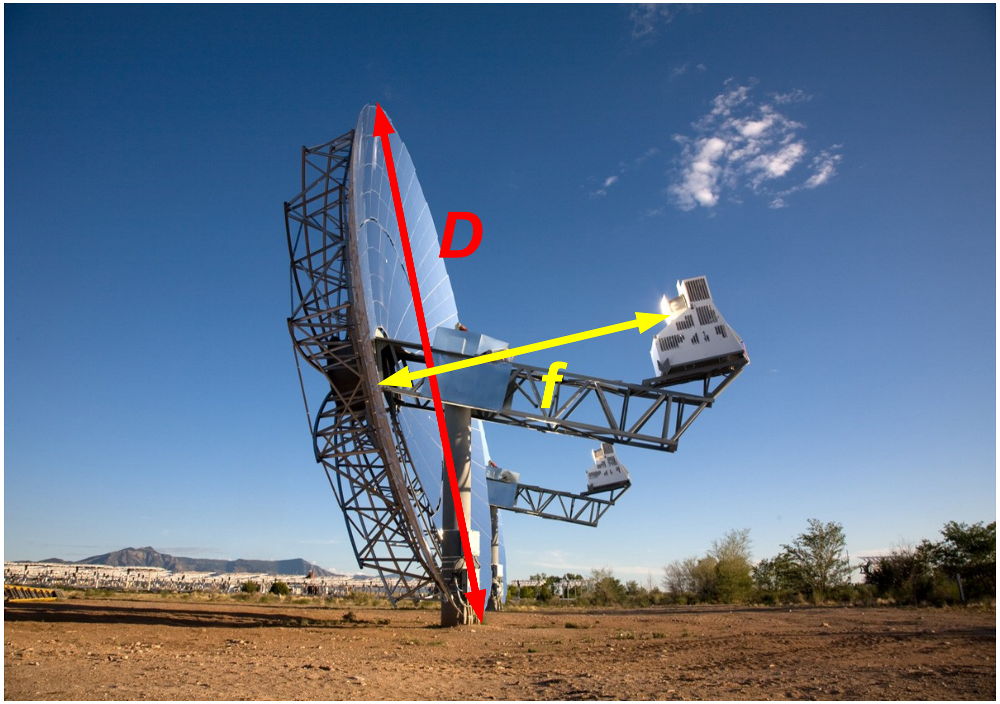
$$\Rightarrow C_S = \frac{D}{2\pi r_A} < \frac{1}{2\pi \sin\theta_S/2} \times \frac{D/f}{\left((D/f)^2/16+1\right)} = \frac{1}{\theta_S} \times \frac{16a}{\pi(a^2+16)}$$

$$C_S(a) < \frac{4}{\pi\ \theta_S} \frac{a/4}{\left((a/4)^2+1\right)}$$

Optimal size?

- CS is maximum for a=D/f=4
- effective in parabolic trough concentrators
- not in 2D collectors (dish / Stirling)

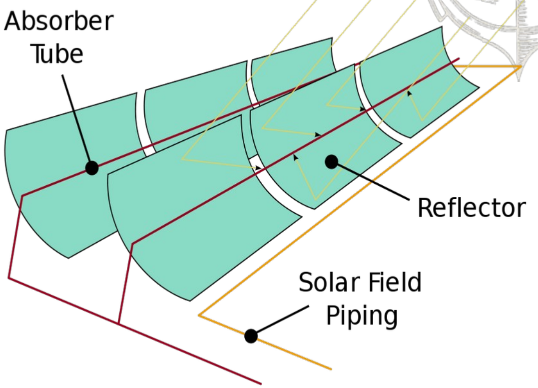


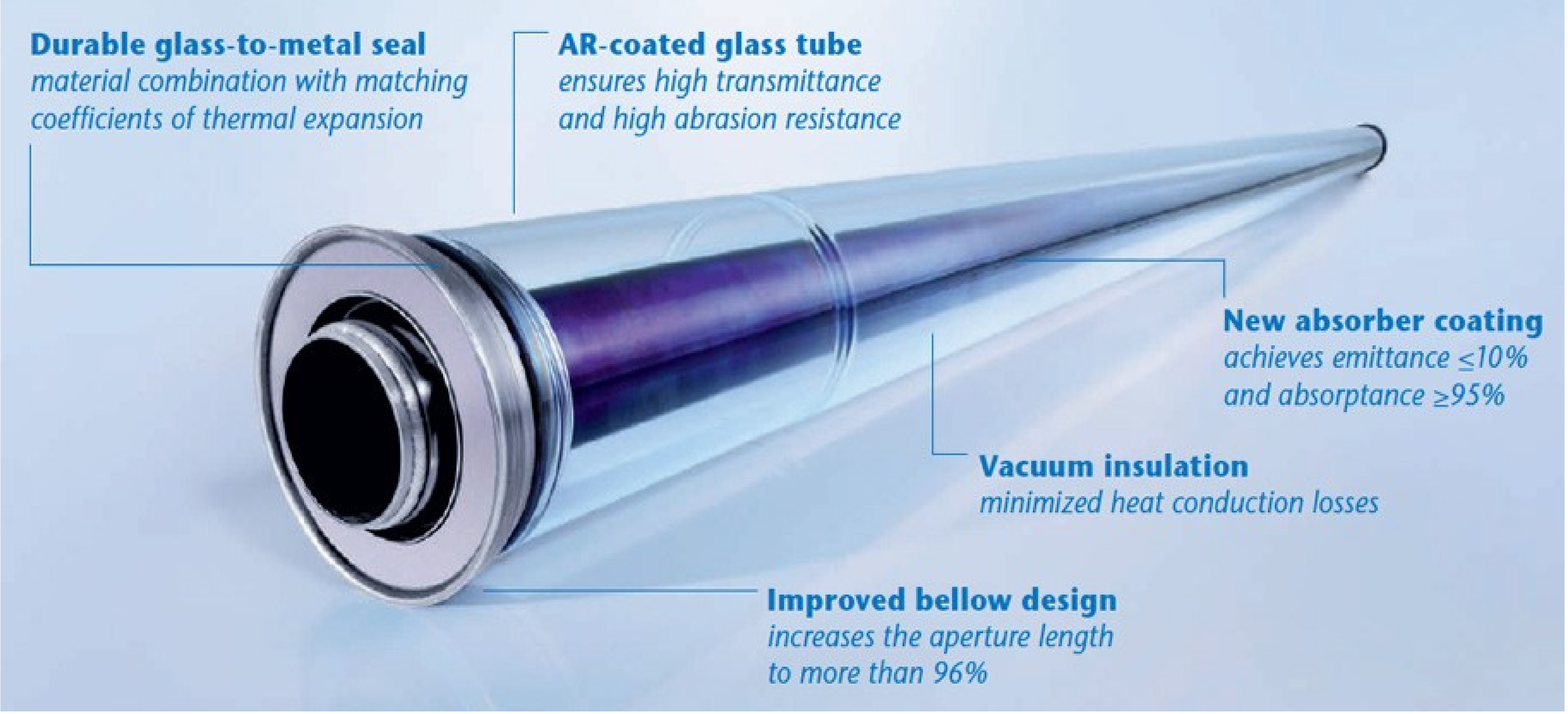


Elements lowering the concentration factor C_S

- All rays do not reach the absorber on normal incidence
  - easy to evaluate, if known absorbency = f (angle of incidence)
- Optical surface defects
  - difficult to assess, need ray tracing
  - Statistical evaluation (RMS deviation from ideal surface)
- Inaccurate pointing at the sun
  - easy to evaluate: partial recovery of the absorber and the image of the sun.
- Imperfect reflectivity of the mirrors
  - easy to evaluate: Fresnel formulas (reflectivity of metals)
- Loss of reflectivity (dust, ageing due to sand)
  - difficult to assess a priori absence of empirical data
- Distortion of the sun image (enlarged) by the atmosphere ("halo")
  - easy to assess if the angular distribution is measured

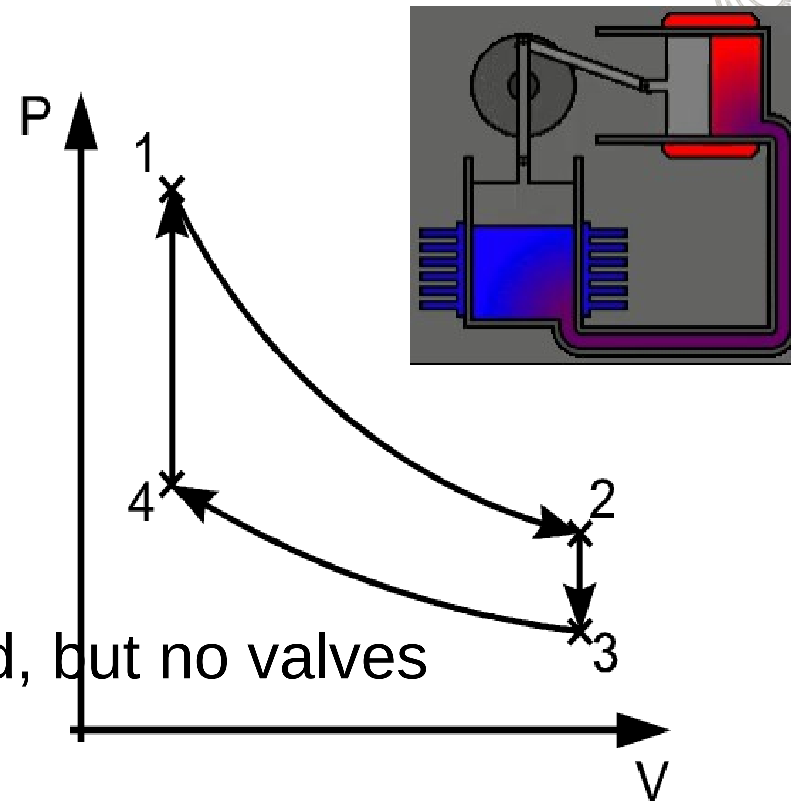
Mitigation of convective losses

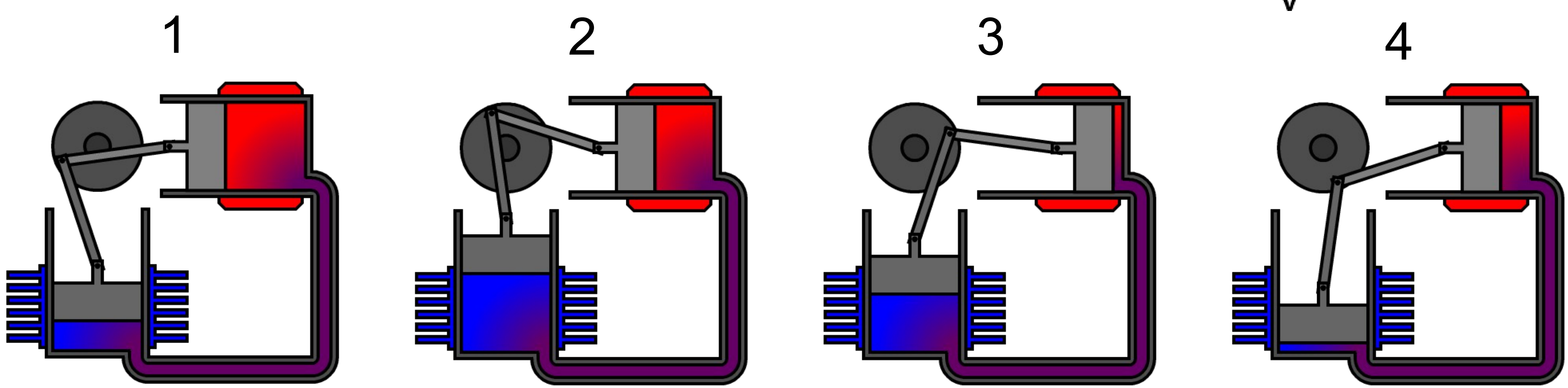




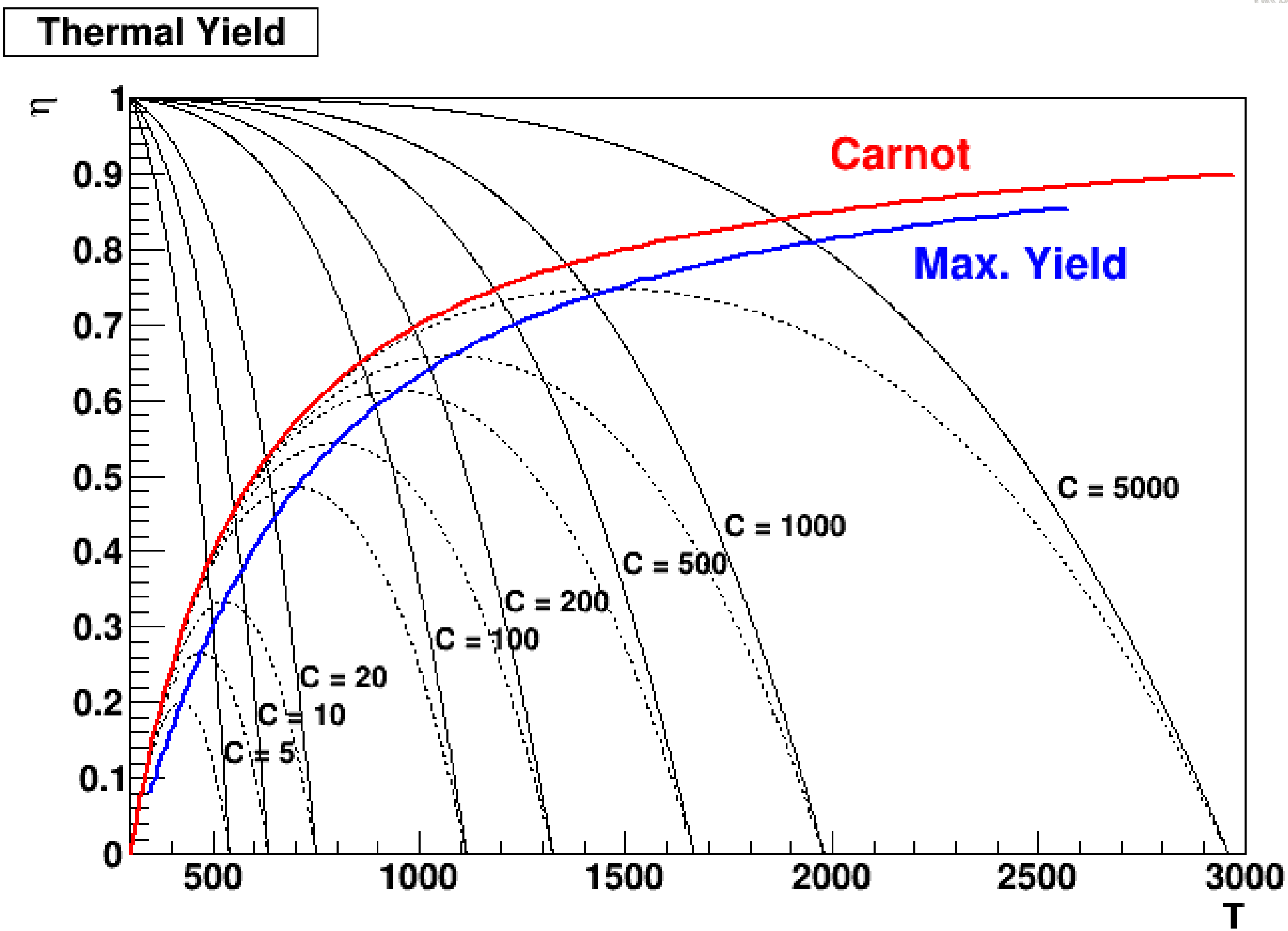
Stirling Engine – Piston engine in closed cycle

- Closed cycle
  - 1-2: isothermal expansion
  - 2-3: isochorous cooling
  - 3-4: isothermal compression
  - 4-1: isochorous heating
- 2 pistons offset by 90º
- external combustion
- mechanically more complicated, but no valves





Final Yield



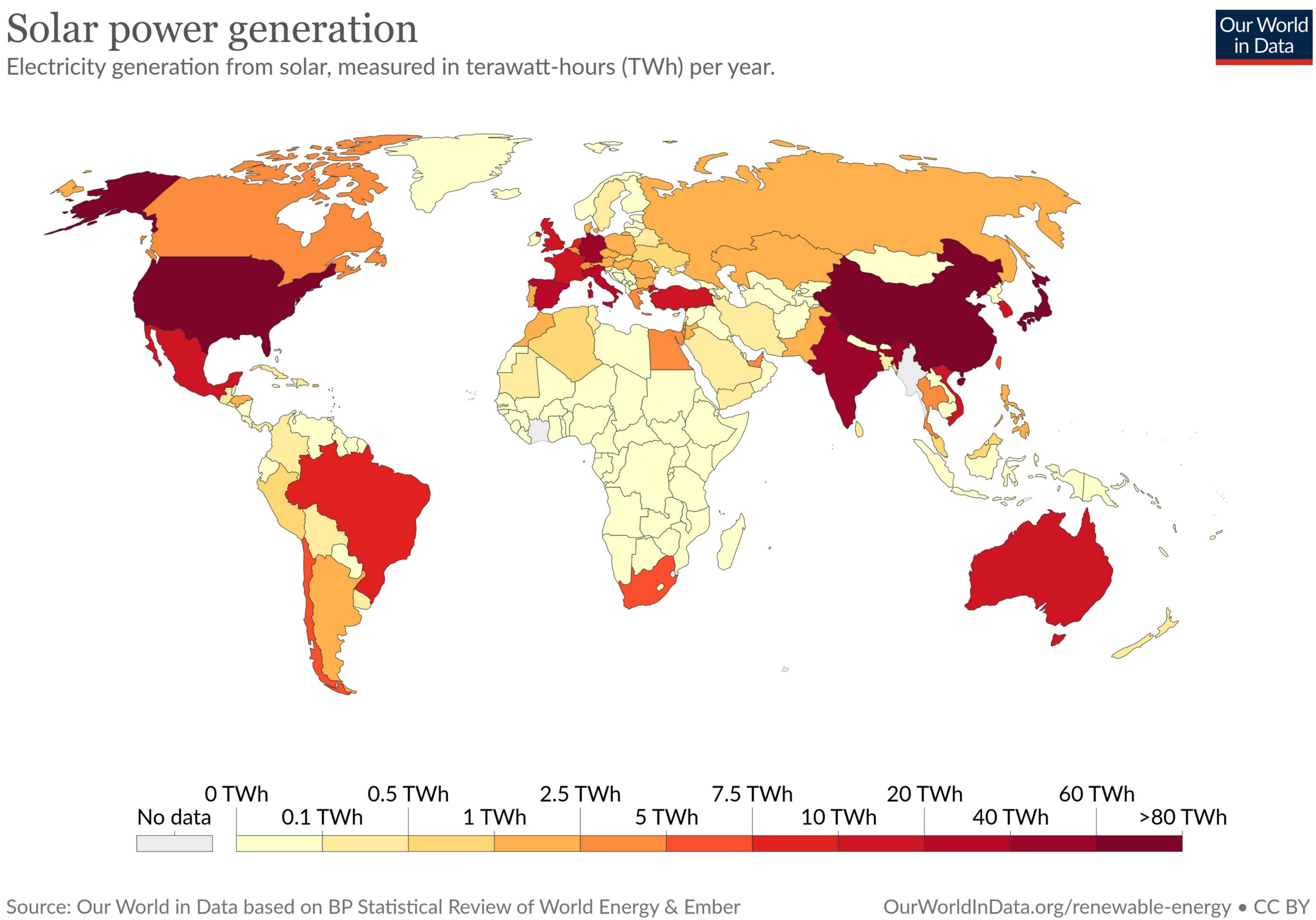
Thermal Yield
η
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
500
1000
1500
2000
2500
3000
T
Carnot
Max. Yield
C = 5000
C = 1000
C = 500
C = 200
C = 100
C = 20
C = 10
C = 5

Comparison of techniques

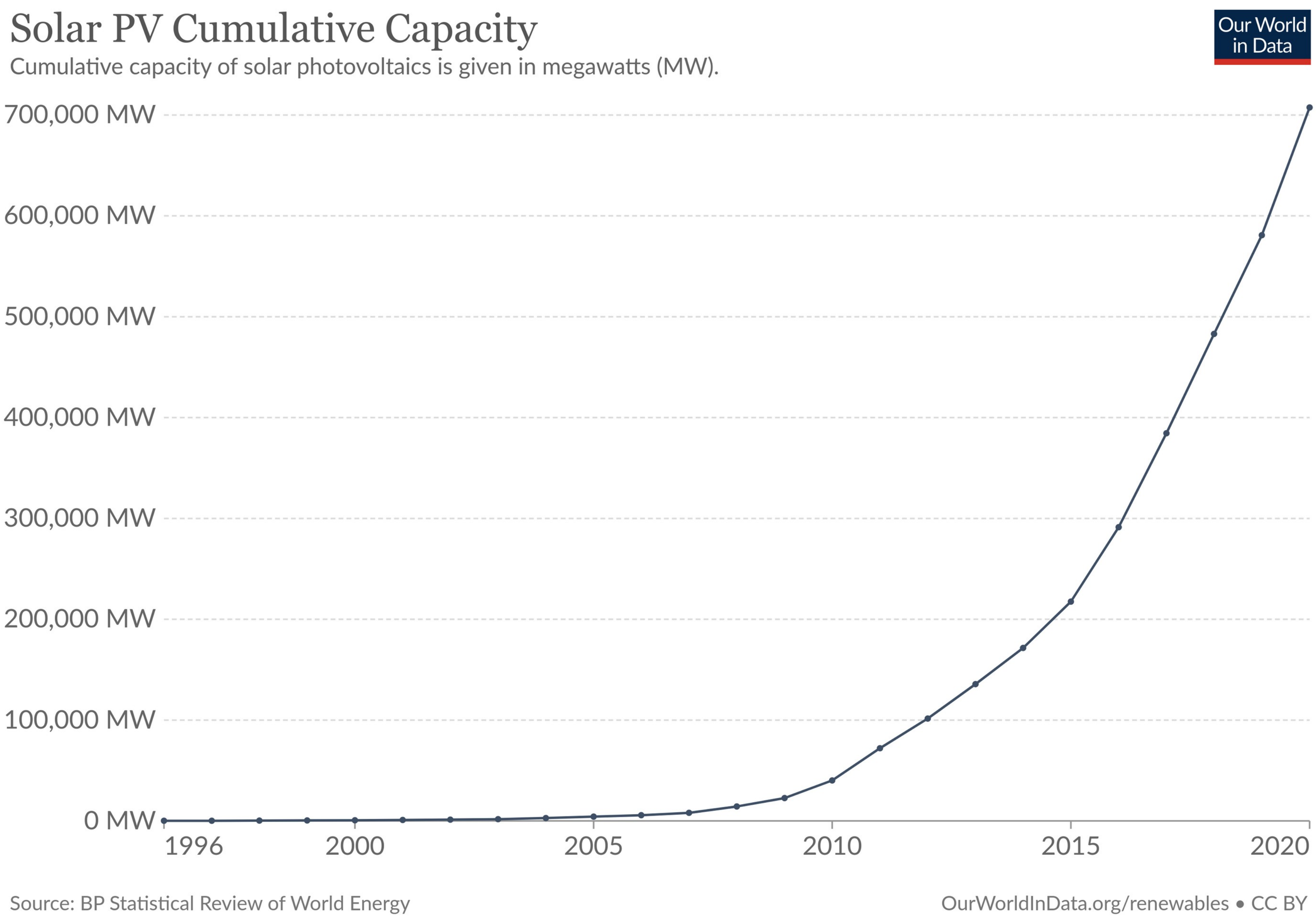
Technology	Cylindrical-parabolic	Tower	Parabola
Nominal thermal efficiency[7]	70%	73%	75%
Power of the installation	80–300 MWth	10–100 MWth	1–100 kWth
Working temperature	270–450°C	450–1,000°C	600–1,200°C
Cost of the solar field[8]	210–250 €/m^2 [9]	140–220 €/m^2	~150 €/m^2
Total cost of the investment	2.8–3.5 €/W_e	3–4 €/W_e	10–14 €/W_e

Table 4.1. *Current characteristics of concentrating devices*

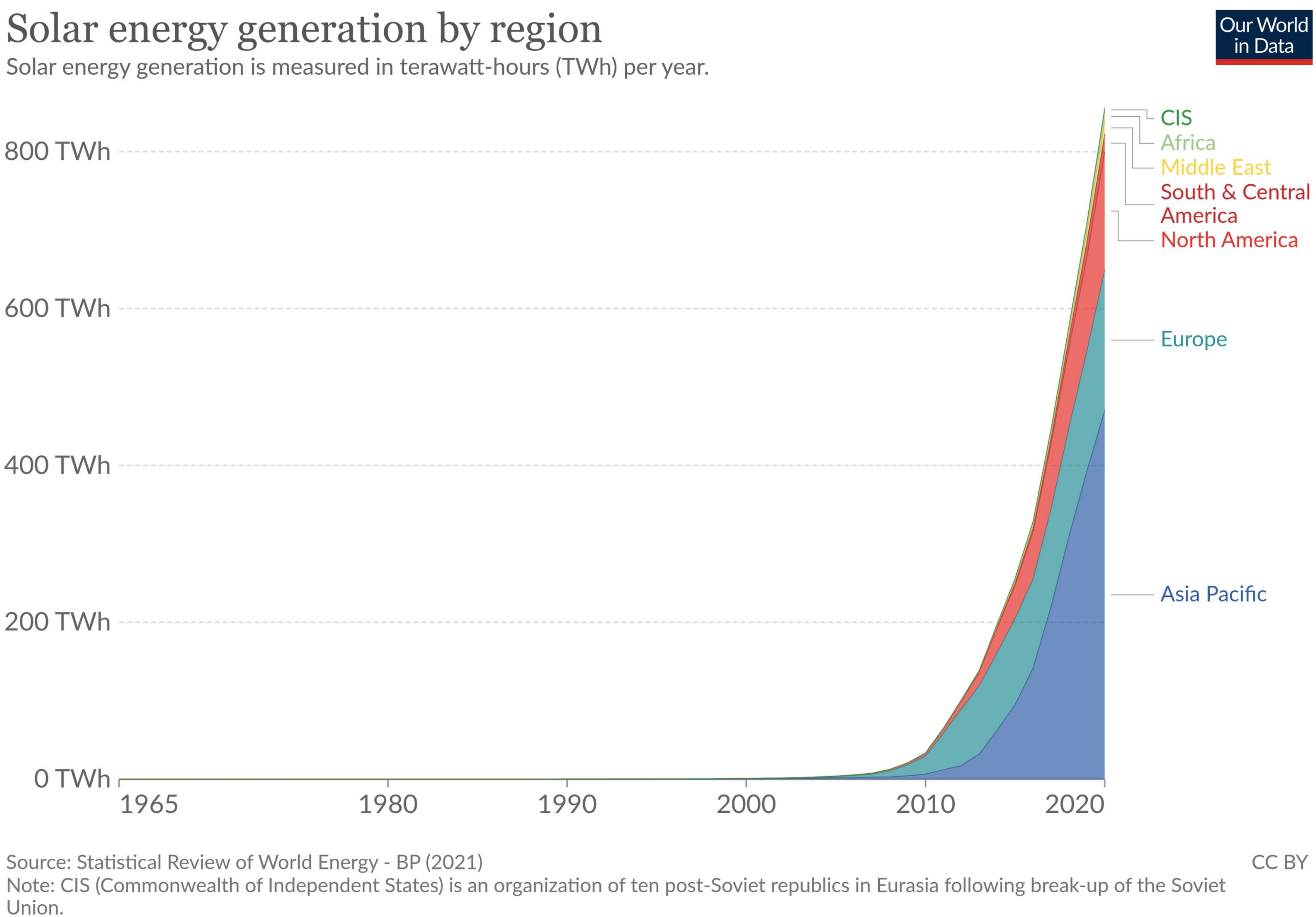
Overall production – 2020



PV Cumulative Capacity



By region


Solar energy generation by region
Solar energy generation is measured in terawatt-hours (TWh) per year.
Our World in Data
800 TWh
600 TWh
400 TWh
200 TWh
0 TWh
1965
1980
1990
2000
2010
2020
CIS
Africa
Middle East
South & Central America
North America
Europe
Asia Pacific
Source: Statistical Review of World Energy - BP (2021)
Note: CIS (Commonwealth of Independent States) is an organization of ten post-Soviet republics in Eurasia following break-up of the Soviet Union.
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Price vs Cumulative Capacity