Solar Energy Conversion Devices and Plants

Prof. Sophia Haussener

Laboratory of Renewable Energy Science and Engineering

Administration

- Course:
  - Monday: 2h lecture (14:15-16:00), PH H3 31
  - Responsible: Prof. Haussener, sophia.haussener@epfl.ch

- Exercise and practical training:
  - Monday, 1h exercises (16:15-17:15), PH H3 31
  - Monday, 4h practical training (14:15-18:00), ME D0 2720
  - Responsible: Venu Agarwal, Paul Feurstein
    Mahendra Patel, Etienne Boutin
- Exercises:
  - Theoretical, small computational projects, laboratory exercises, and one group project

- Exam: written (34%), computational projects (22%), laboratory report (22%), group project report (22%);

  written: only calculator and 10-pages (A4, single sided) personal summary

  computational: two out of three computational exercises (no group work)

  practical training: one laboratory report for practical trainings (teams of 2 members)

  group project: one 3-page report on solar energy technology/product (teams of 2-4 members)

Administration

- **Prerequirements**
- Knowedlge in numerical techniques and programming (Monte Carlo, Finite differences)
- Knowledge in thermodyanmics, heat transfer, semiconductor physics, chemistry

Course structure

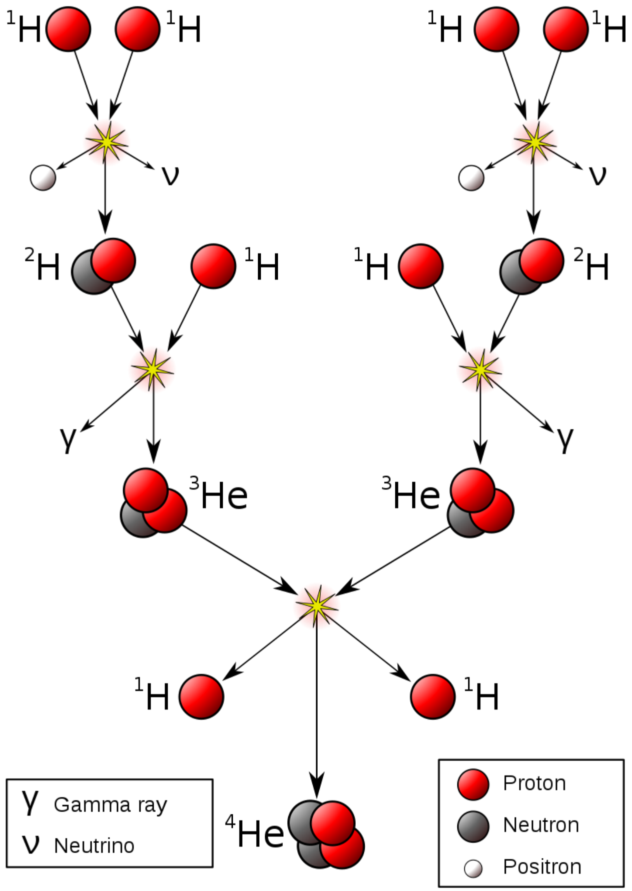
	Lecture	Exercise
Week 1	Introduction: Solar energy characteristics, solar energy conversion	Exercise 1 – group project
Week 2	Energy states in matter, basics in thermal transport, exergy analysis in solar systems	Exercise 2
Week 3	No lecture	
Week 4	Technology: Solar thermal collectors	Exercise 3
Week 5	Basics in optics, concentrating technologies, solar thermal (high-temp)	Computational exercise 1
Week 6	Solar electricity - CSP	Exercise 4
Week 7	Basics in semiconductors, junctions	Exercise 5
Week 8	Solar electricity - PV	Computational exercise 2
Week 9	Basics in thermochemistry, solar fuels by thermochemical path	Exercise 6
Week 10	Basics in electrochemistry (low and high-temperature)	Computational exercise 3
Week 11	Electrochemistry lab 1	
Week 12	Electrochemistry lab 2	
Week 13	Solar fuels by photo-eletctrochemical, photocatalysis	Exercise 7
Week 14	Special topics: thermoelectrics thermophotovoltaics	Exercise 8

Introduction

- Solar energy and sun characteristics

Solar energy / Solar characteristics

- Solar energy originates from fusion in the sun:
  - Reaction that converst mass in energy by converting small elements in heavier elements
  - So called proton-proton cycle:
    - $^{1}H + {}^{1}H \rightarrow {}^{2}H + e^{+} + \nu$
    - $e^{-} + e^{+} \rightarrow 2\gamma$ (annihilation, very fast)
    - $^{2}H + {}^{1}H \rightarrow {}^{3}He + \gamma$
    - $^{3}He + {}^{3}He \rightarrow {}^{6}Be$ (fast)
    - $^{6}Be \rightarrow {}^{4}He + {}^{1}H + {}^{1}H$
  - In net: $4\,{}^{1}H + 2e^{-} \rightarrow {}^{4}He + 2\nu + 6\gamma$



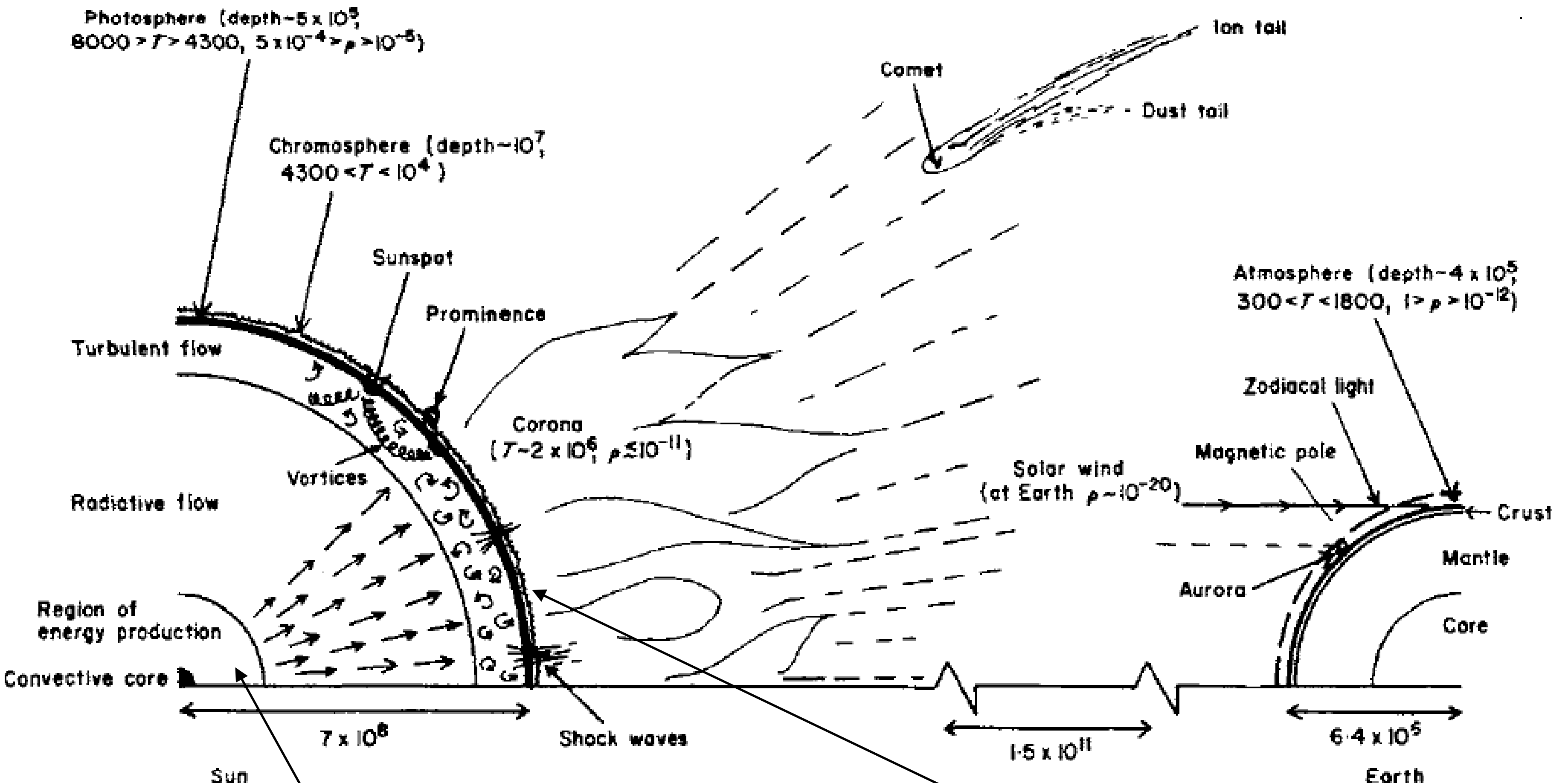
ν : Neutrino
γ : Gamma photons
e^{+} : positron
^{3}He: Helium isotope
^{4}He: Helium
^{1}H : Hydrogen nuclei / proton

Solar energy / Solar characteristics

- Solar energy originates from fusion in the sun:
  - In net, fusion reaction in sun:
    $4\,{}^{1}H + 2e^{-} \rightarrow {}^{4}He + 2\nu + 6\gamma$
  - Mass:
    $6.693 \cdot 10^{-27}$ kg + $1.8 \cdot 10^{-30}$ kg $\rightarrow$ $6.645 \cdot 10^{-27}$ kg + 0 kg + 0kg
  - Missing mass, $-\Delta m$: $4.98 \cdot 10^{-29}$ kg
  - Resulting energy, $E=mc^2$: $4.5 \cdot 10^{-12}$ J
  - Specific energy density (per reactant mass): $6.5 \cdot 10^{14}$ J/kg
    (Compared to gasoline: $5 \cdot 10^{7}$ J/kg)

Solar energy / Solar characteristics

- Solar energy originates from fusion in the sun



Region of energy production:
25% of sun's radius
40% of sun's mass
10^7K estimated temperature

5800 K estimated surface temperature

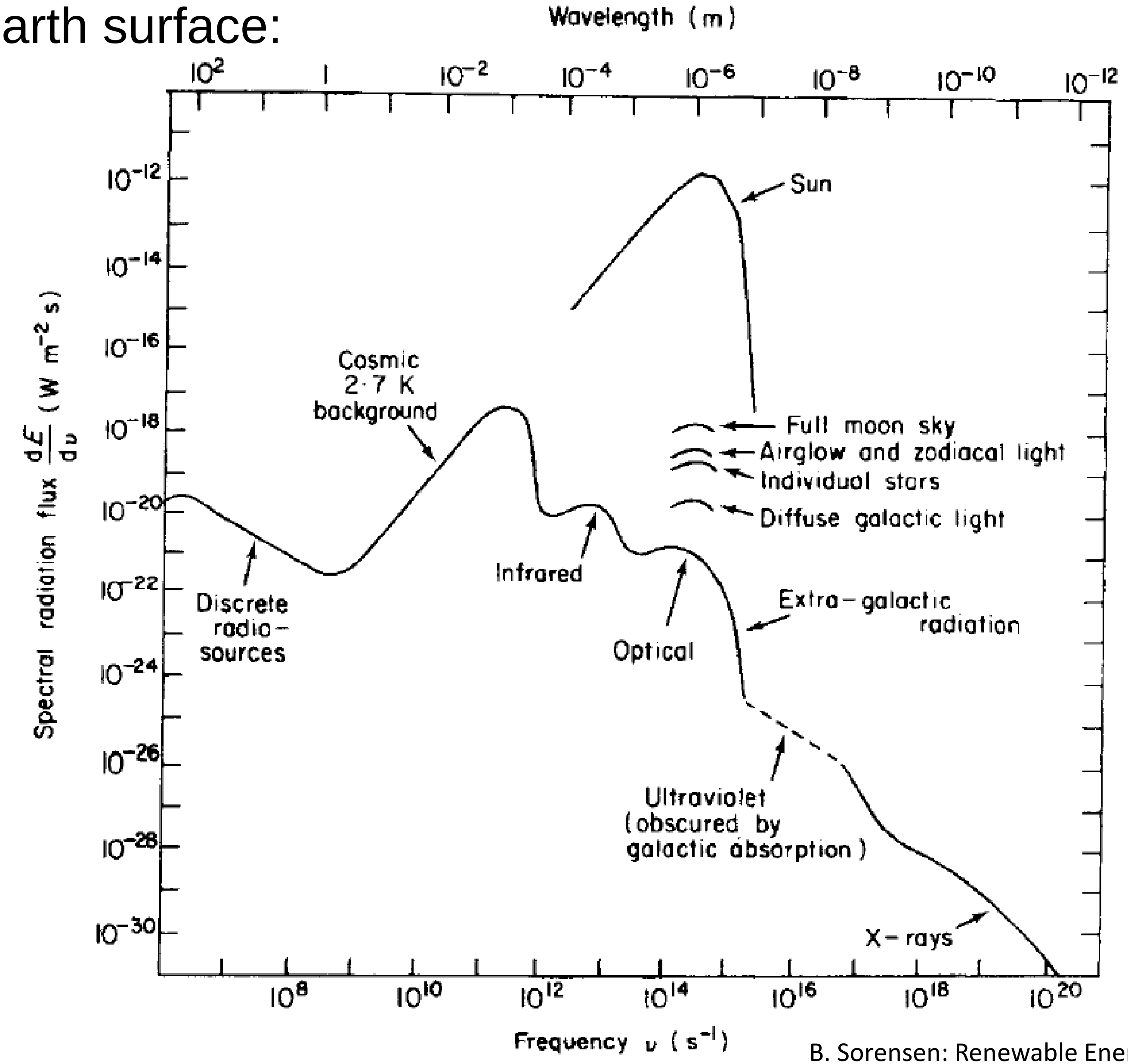
B. Sorensen: Renewable Energy, 2004

Solar energy / Solar characteristics

- Solar energy originates from fusion in the sun

Solar energy / Solar characteristics

- Radiation at earth surface:



B. Sorensen: Renewable Energy, 2004

Solar energy / Solar characteristics

- Solar radiation at earth surface:
  - Wavelength distribution:
    Close to black body at 5780 K: $E_{b\lambda}(T,\lambda) = \dfrac{C_1}{n^2\lambda^5\left[e^{C_2/(n\lambda T)} - 1\right]}$
    (Planck's law)

C_1 First radiation constant $\left(\begin{aligned} &= 2\pi h c_0^2 = 3.7418\text{x}10^{-16}\ \text{W m}^2 \\ &= 3.7418 \times 10^8\ \text{W}\,\mu\text{m}^4\text{m}^{-2} \end{aligned}\right)$

C_2 Second radiation constant $\left(= hc_0 / k = 14{,}388.69\ \mu\text{m K}\right)$

h Planck constant $\left(= 6.6260755 \times 10^{-34}\ \text{Js}\right)$

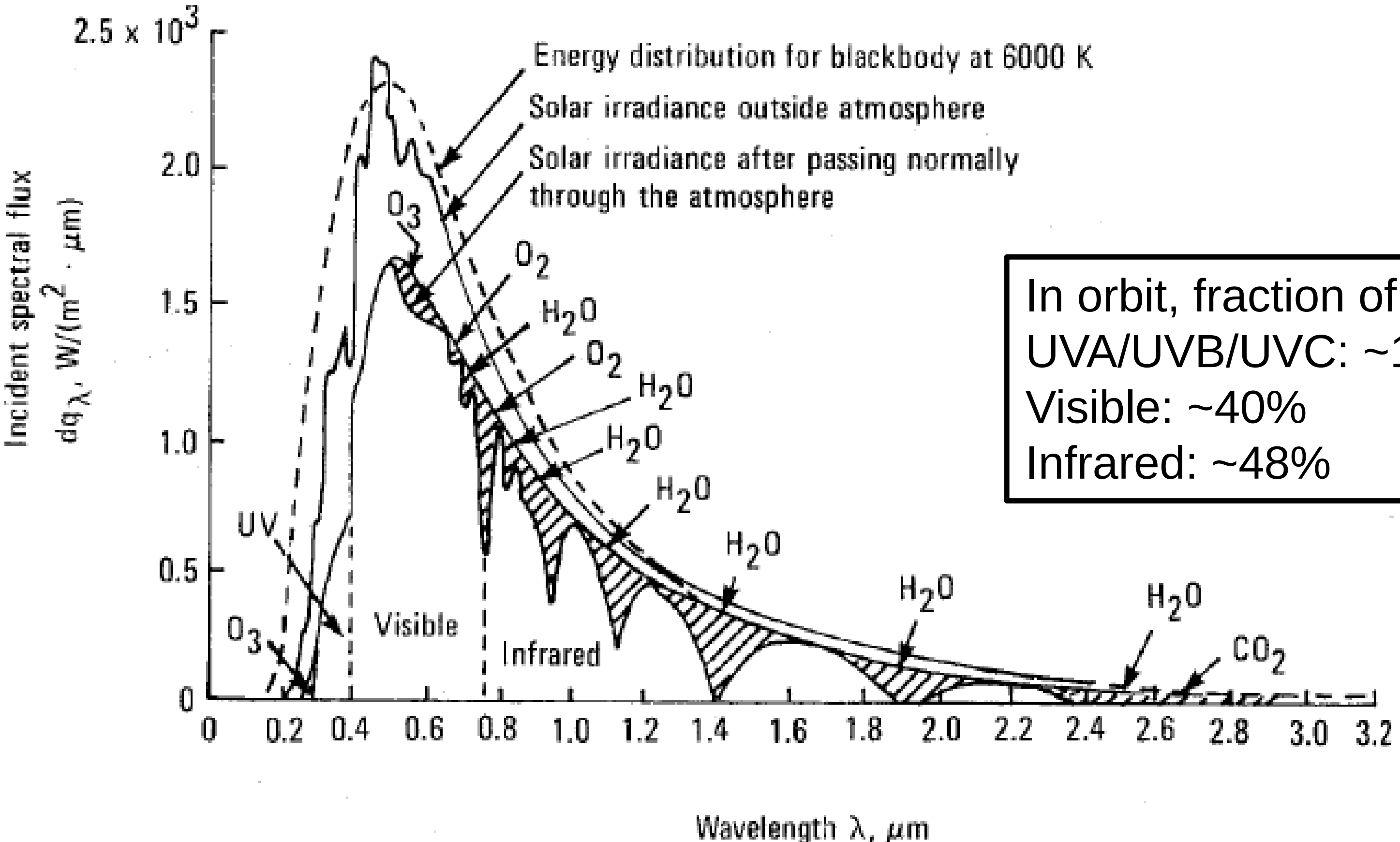
c_0 speed of light in vacuum $\left(= 2.998 \times 10^8\ \text{m s}^{-1}\right)$

k Boltzmann constant $\left(= 1.380658 \times 10^{-23}\ \text{JK}^{-1}\right)$

Solar energy / Solar characteristics

- Solar radiation at earth surface:
  - Wavelength distribution:
    Close to black body at 5780 K:
    (Planck's law)

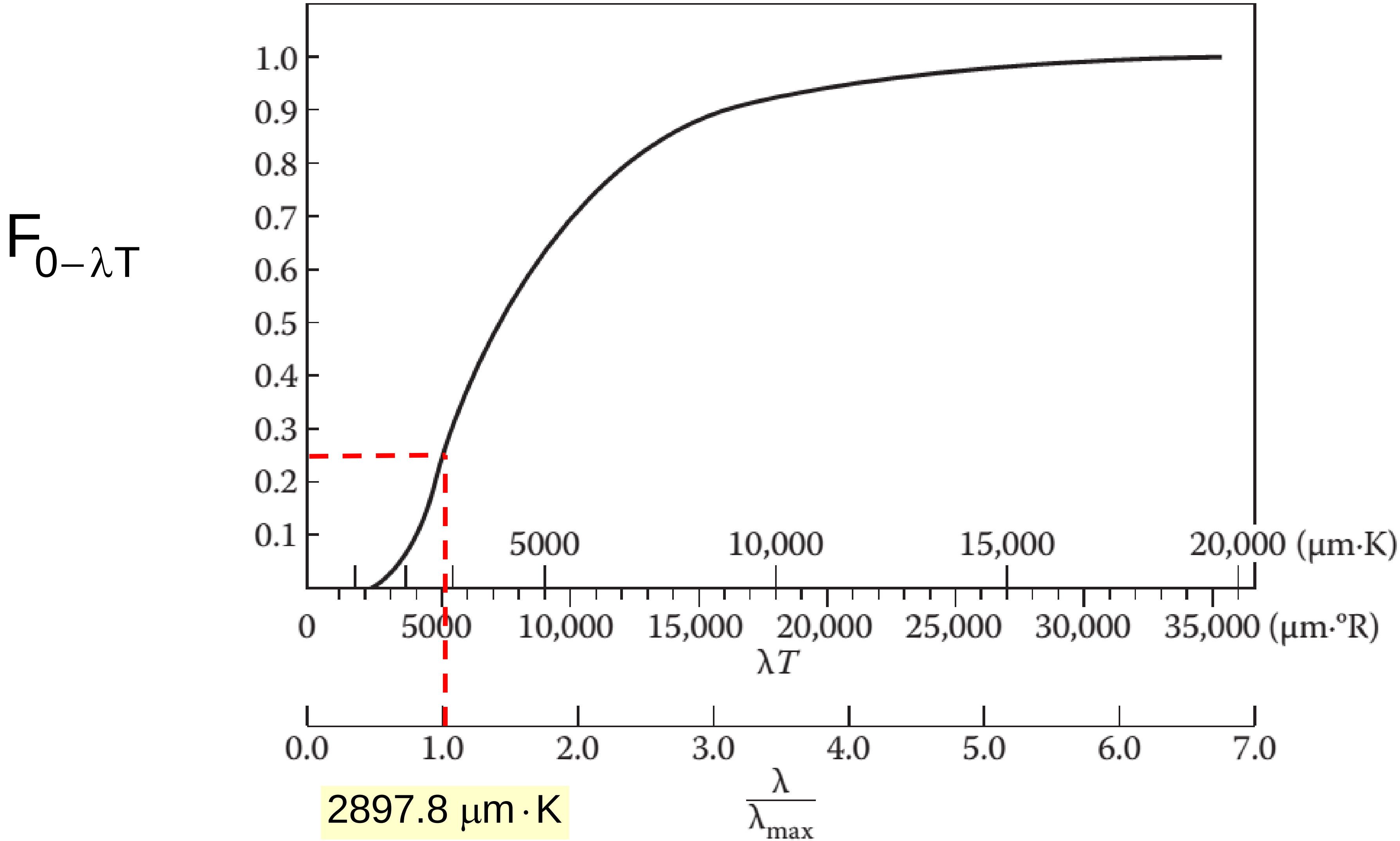
$$E_{b\lambda}(T,\lambda) = \frac{C_1}{n^2\lambda^5\left[e^{C_2/(n\lambda T)} - 1\right]}$$



In orbit, fraction of solar radiation in:
UVA/UVB/UVC: ~12%
Visible: ~40%
Infrared: ~48%

Solar energy / Solar characteristics

- Cummulative:



Solar energy / Solar characteristics

- Fractional function of black body:

$$f(n\lambda T) = f_{0-n\lambda T} = \frac{\int_0^{\lambda} E_{b\lambda}(T,\lambda)\,d\lambda}{\int_{\lambda=0}^{\infty} E_{b\lambda}(T,\lambda)\,d\lambda} = \frac{\int_0^{\lambda} E_{b\lambda}(T,\lambda)\,d\lambda}{n^2\sigma T^4} = \int_0^{n\lambda T} \frac{E_{b\lambda}(T,\lambda)}{n^3\sigma T^5}\,d(n\lambda T)$$

$$= \frac{15}{\pi^4}\int_{\xi=C_2/(n\lambda T)}^{\infty} \frac{\xi^3\,d\xi}{e^{\xi}-1} = \frac{15}{\pi^4}\sum_{m=1}^{\infty}\left[\frac{e^{-m\xi}}{m}\left(\xi^3 + \frac{3\xi^2}{m} + \frac{6\xi}{m^2} + \frac{6}{m^3}\right)\right]$$

- Wien's law: $(n\lambda T)_{max} = C_3 = 2897.8\ \mu mK$

Solar energy / Solar characteristics

- Fractional function of black body – make your own function:

```
function [c]=fract(ref,lambda,temp,nmax=100)
h=6.62607004e-34; % m2 kg / s
c0=299792458; % m / s
k=1.38064852e-23; % m2 kg s-2 K-1
C2=h*c0/k;

zeta = C2/(ref*lambda*temp);

for i = 1:nmax; % nmax=15
     b(i) = exp(-
i*zeta)/i*(zeta^3+3.0*zeta^2/i+6.0*zeta/i^2+6.0/i^3);
end

c = sum(b)*15.0/pi^4;
```

- Inverse of fractional function of black body:

$$\lambda T = D_1 + D_2 R_\lambda^{1/8} + D_3 R_\lambda^{1/4} + D_4 R_\lambda^{3/8} + D_5 R_\lambda^{1/2} \qquad 0.0 < R_\lambda < 0.1$$

$$\lambda T = D_1 + D_2 R_\lambda + D_3 R_\lambda^2 + D_4 R_\lambda^3 + D_5 R_\lambda^4 \qquad 0.1 < R_\lambda < 0.9$$

$$\lambda T = \left[\frac{0.152886 \times 10^{12}}{D_1(1 - R_\lambda) + D_2(1 - R_\lambda)^2 + D_3(1 - R_\lambda)^3 + D_4(1 - R_\lambda)^4}\right]^{1/3} \qquad 0.9 < R_\lambda < 1$$

Range of R_λ	Coefficients D_1	D_2	D_3	D_4	D_5
0.0–0.1	503.247	230.243	5,863.85	−10,759.6	8,723.14
0.1–0.4	1,560.84	7,603.61	−15,540.1	31,257.7	−20,844.8
0.4–0.7	2,846.63	−4,430.38	27,936.0	−41,041.9	25,960.9
0.7–0.9	345,197	−1,828,567	3,674,856	−3,284,391	1,108,939
0.9–0.99	1.200	9.476	−44.84	156.9	—
0.99–1.0	1.10064	16.8148	−183.445	890.699	—

Solar energy / Solar characteristics

- Inverse of fractional function of black body – make your own function:

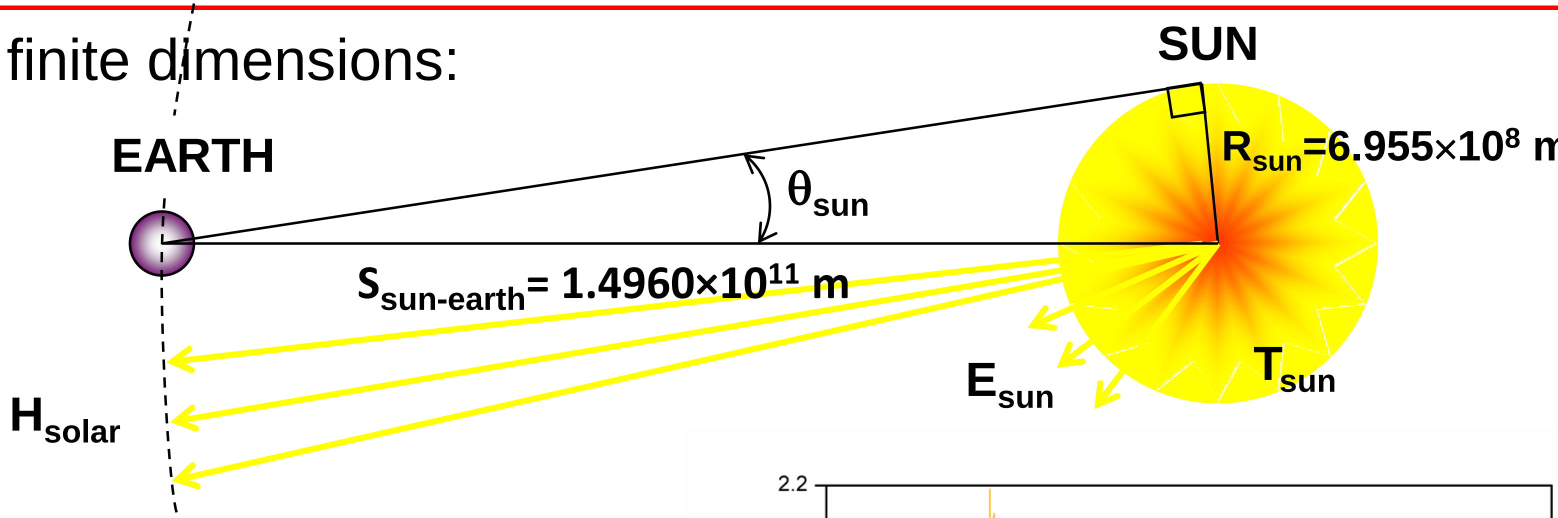
```
function [c]=inv_fract(RR)

D1=[503.247 1560.84 2846.63 345197 1.2 1.10064];
D2=[230.243 7603.61 -4430.38 -1828567 9.476 16.8148];
D3=[5863.85 -15540.1 27936 3674856 -44.48 -183.445];
D4=[-10759.6 31257.7 -41041.9 -3284391 156.9 890.699];
D5=[8723.14 -20844.4 25960.9 1108939 0 0];

if(RR<0.1);
    c=D1(1)+D2(1)*RR^(1/8)+D3(1)*RR^(1/4)+D4(1)*RR^(3/8)+D5(1)*RR^(1/2);
elseif(RR<0.9);
    if(RR<0.4);
        c=D1(2)+D2(2)*RR^(1)+D3(2)*RR^(2)+D4(2)*RR^(3)+D5(2)*RR^(4);
    elseif(RR<0.7);
        c=D1(3)+D2(3)*RR^(1)+D3(3)*RR^(2)+D4(3)*RR^(3)+D5(3)*RR^(4);
    else;
        c=D1(4)+D2(4)*RR^(1)+D3(4)*RR^(2)+D4(4)*RR^(3)+D5(4)*RR^(4);
    end
else
    if(RR<0.99);
        c=((0.152886*10^(12))/(D1(5)*(1-RR)+D2(5)*(1-RR)^2+D3(5)*(1-RR)^3+D4(5)*(1-RR)^4))^(1/3);
    else
        c=((0.152886*10^(12))/(D1(6)*(1-RR)+D2(6)*(1-RR)^2+D3(6)*(1-RR)^3+D4(6)*(1-RR)^4))^(1/3);
    end
end
```

Solar energy / Solar characteristics

- Sun has finite dimensions:



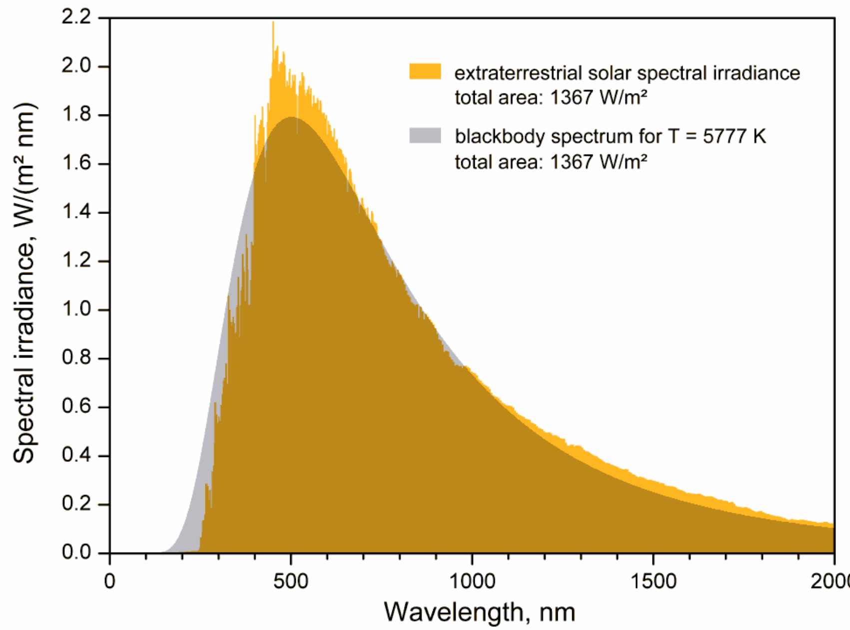
$$\theta_{sun} = \operatorname{asin}\left(\frac{R_{sun}}{S_{sun-earth}}\right) = 4.65\,\text{mrad} = 0.267°$$

$$\dot{Q}_{sun} = E_b\left(T_{sun}\right)A_{sun} = \sigma T^4 4\pi R_{sun}^2$$

$$= \dot{q}_{solar} A_{orbit} = \dot{q}_{solar} 4\pi S_{sun\text{-}earth}^2$$

$$\dot{q}_{solar} = \underbrace{\left(\frac{R_{sun}}{S_{sun\text{-}earth}}\right)^2}_{C} E_b\left(T_{sun}\right)$$

$$= C\int_{\lambda=0}^{\infty} E_{b\lambda}(T_{sun},\lambda)\,d\lambda = C\sigma T_{sun}^4 \approx 1360\,W/m^2 = 1366\,W/m^2\left(1+0.033\cos\left(\frac{360°n}{365}\right)\right)$$

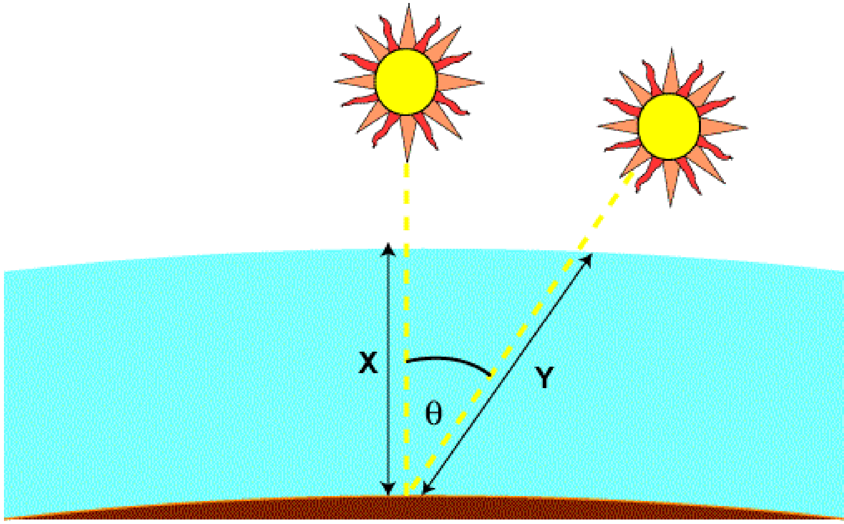


Solar energy / Solar characteristics

- Definitions:
  - Air mass (AM):

    AM is the path length which light travels through the atmosphere normalized to the shortest possible path length (sun is directly overhead).

    AM quantifies the reduction in the power of light as it passes through the atmosphere and is absorbed by air and dust:



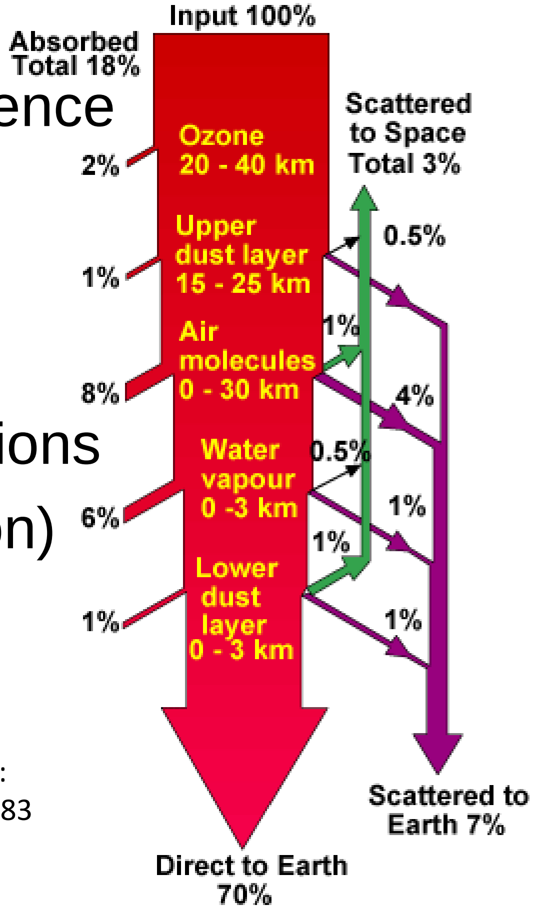
$$AM = \frac{1}{\cos\theta} = \frac{Y}{X}$$

  - AM0: solar spectrum outside of the atmosphere with 1353 W/m^2
  - AMx defines both the spectrum and the power density
  - AM1.5D = only direct radiation, normalized at 900 W/m^2
  - AM1.5G = including diffuse radiation, normalized at 1000 W/m^2

Solar energy / Solar characteristics

- Solar radiation at earth surface:
  - Effect of the atmosphere on power, spectrum and directionality
    - Power reduction due to absorption, scattering and reflection in the atmosphere
    - Spectral changes due wavelength-dependence of extinction
    - New diffuse component
  - Varies locally according to atmospheric conditions (e.g. such as water vapor, clouds and pollution)
  - For direct (beam) irradiation:

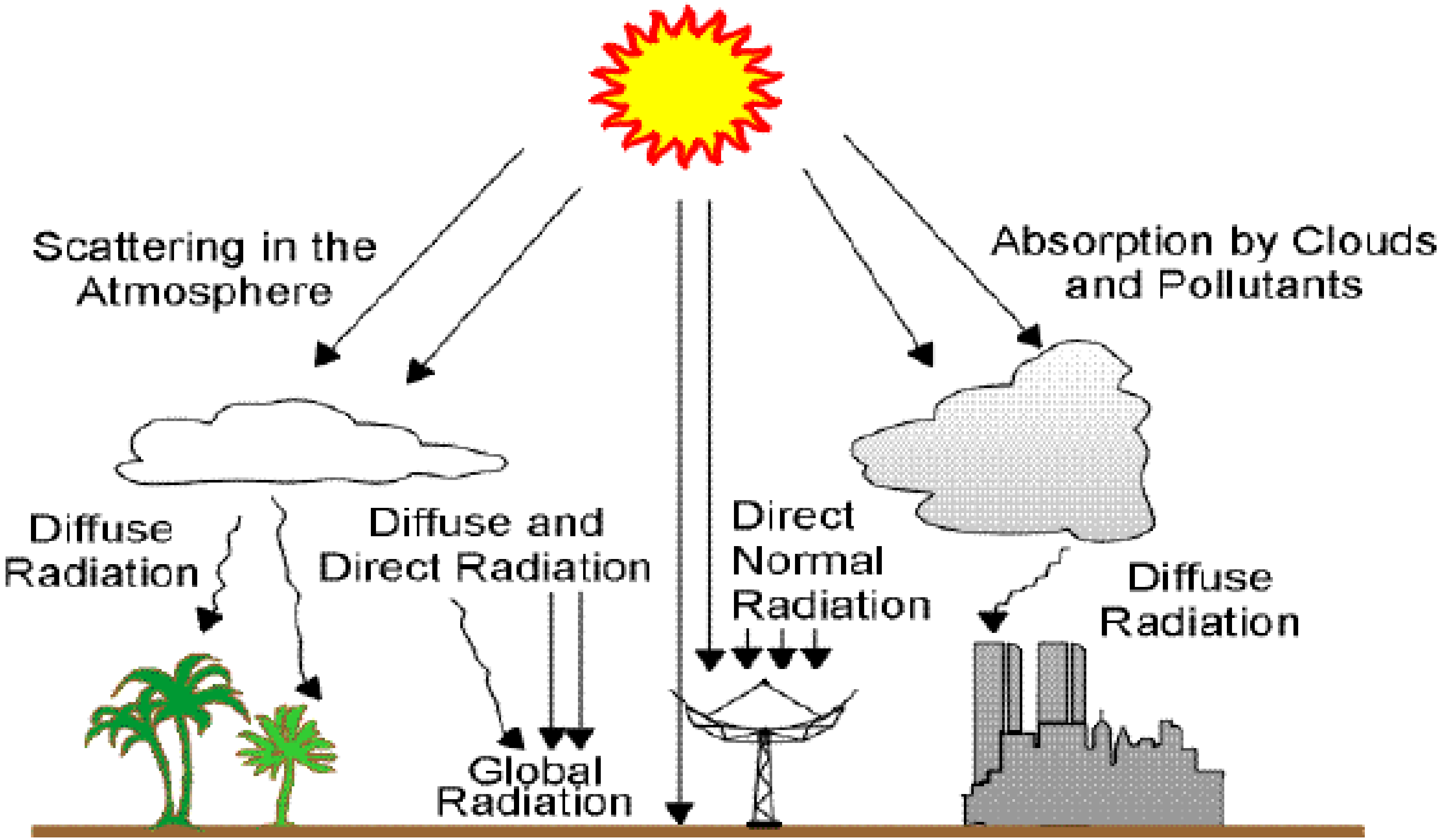
$$B_{ter} = \tau \cdot \dot{q}_{solar}$$



Hu and White: Solar Cells, 1983

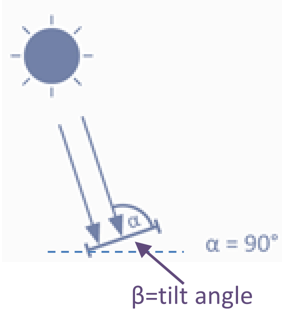
Solar energy / Solar characteristics

- Not all radiation can be used by all conversion technologies

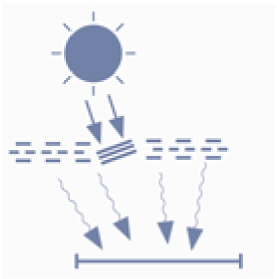


Solar energy / Solar characteristics

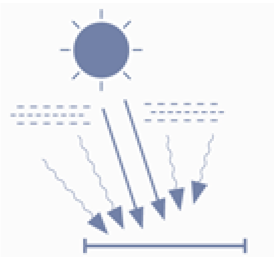
- **Direct Normal Irradiance** (DNI), or *beam radiation*, measured at the surface of the Earth at a given location with a surface element perpendicular to the Sun. It excludes diffuse solar radiation (radiation that is scattered or reflected by atmospheric components). Direct irradiance is equal to the extraterrestrial irradiance above the atmosphere minus the atmospheric losses due to absorption and scattering. Losses depend on time of day (length of light's path through the atmosphere depending on the solar elevation angle), cloud cover, moisture content and other contents.



- **Diffuse Horizontal Irradiance** (DHI), or *Diffuse Sky Radiation* is the radiation at the Earth's surface from light scattered by the atmosphere. It is measured on a horizontal surface with radiation coming from all points in the sky excluding *circumsolar radiation* (radiation coming from the sun disk). There would be almost no DHI in the absence of atmosphere.



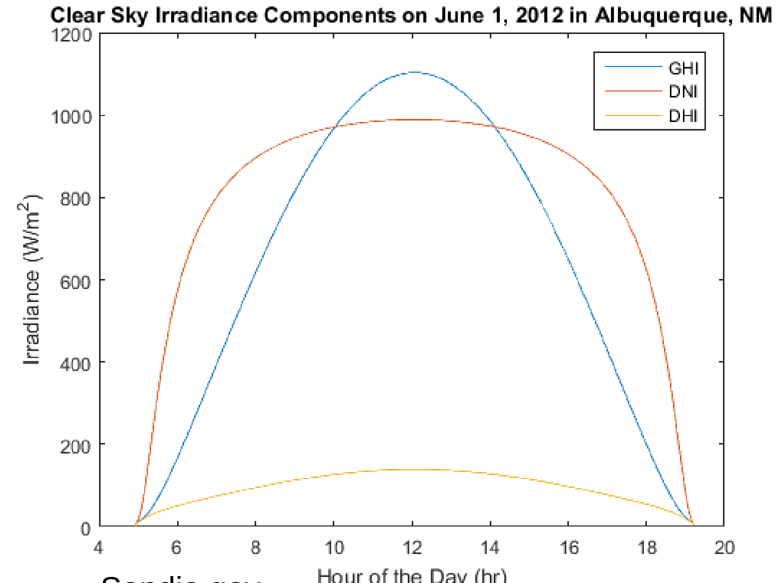
- **Global Horizontal Irradiance** (GHI) is the total irradiance from the sun on a horizontal surface on Earth. It is the sum of direct irradiance (after accounting for the solar zenith angle of the sun θ) and diffuse horizontal irradiance.



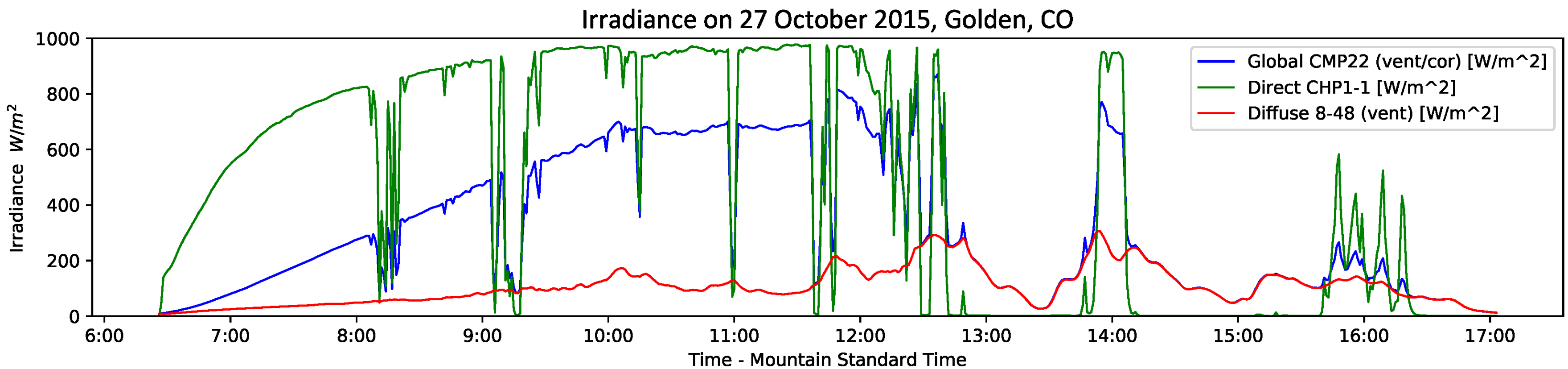
Solar energy / Solar characteristics

- Relation between GHI, DNI, DHI:

$$GHI = DHI + DNI \cdot cos(\theta)$$

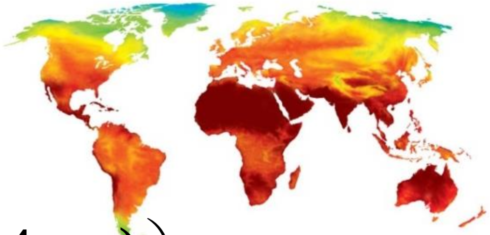


Sandia.gov



Moncada et al., Energies, doi: 0.3390/en11081988, 2018

Solar energy / Solar characteristics

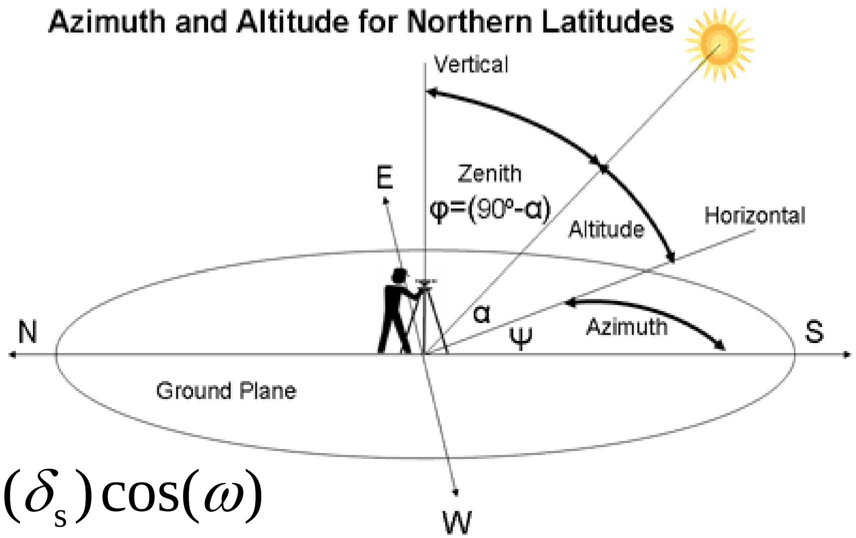


- Spatial and temporal distribution
  - Local position:
    - ϕ: latitude angle
    - δ_s: solar declination, $\delta_s = 23.45° \sin\left(\frac{360(284+n)}{365}\right)$, n = 1 ... 365
    - ST: solar time
    - ω: hour angle, ω = 15(ST-12)
  - Sun position:
    - ψ: solar azimuth angle,

$$\sin(\psi) = \frac{\cos(\delta_s)\sin(\omega)}{\cos(\alpha)}$$

    - α: solar altitude angle,

$$\sin(\alpha) = \sin(\phi)\sin(\delta_s) + \cos(\phi)\cos(\delta_s)\cos(\omega)$$



Solar energy / Solar characteristics

- Spatial and temporal distribution
  - Local position:
    - ϕ: latitude angle: angle between a line from the center of the earth to the site of interest and the equatorial plane. Values north of equator are positive and those south are negative, [-90°,90°]

    - δ_s: solar declination: angular position of the sun at solar noon with respect to the plane of the equator. Declinations are positive in northern hemisphere and negative in southern hemisphere,

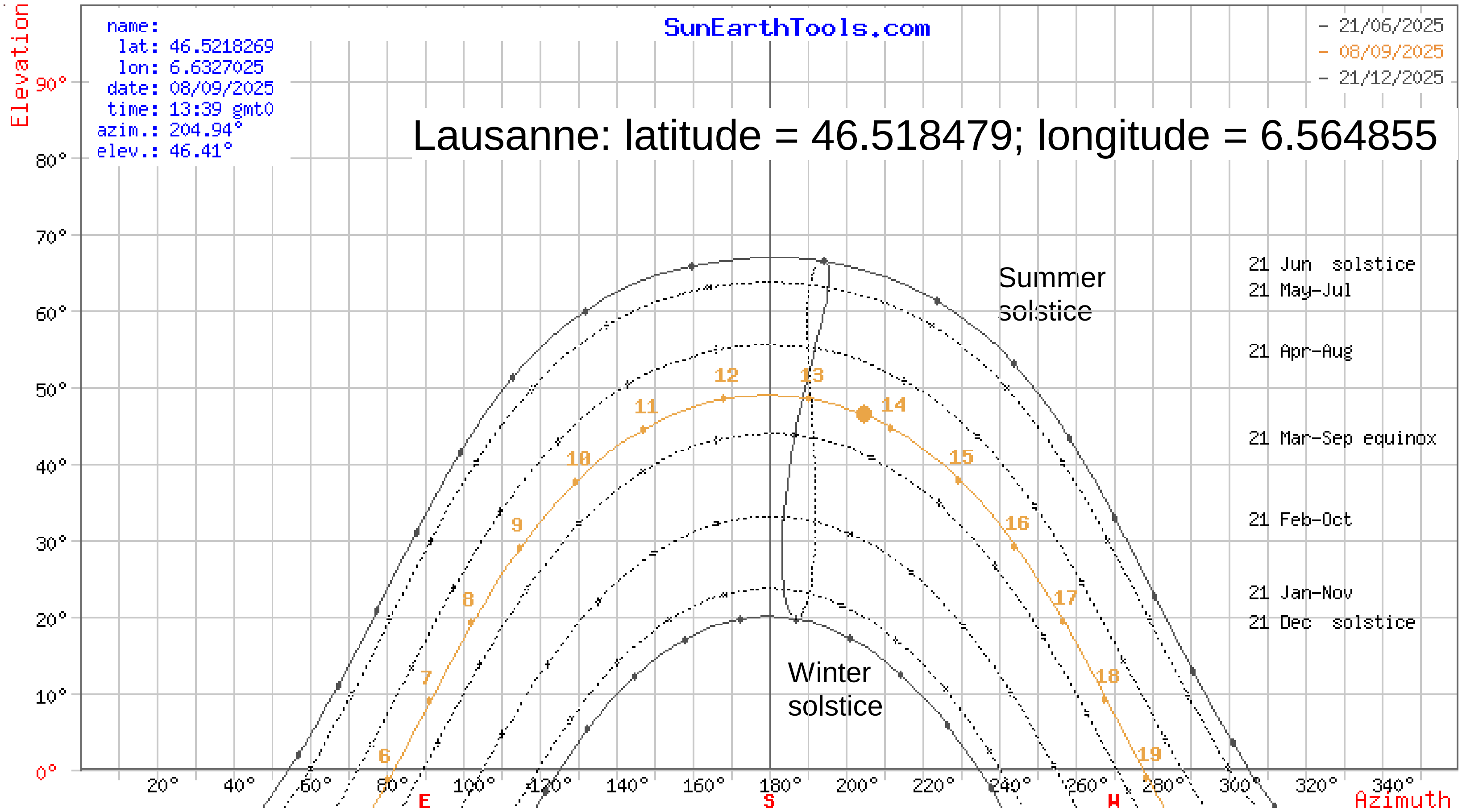
      [-23.45°,23.45°]

    - ω: hour angle: angular displacement of the sun east or west of the local meridian, based on the nominal time of 24 hours for the sun to travel 360°, or 15° per hour. When the sun is due south for northern hemisphere (due north for southern hemisphere), the hour angle is 0, morning values are negative, afternoon values are positive

Solar energy / Solar characteristics

- Today's sun position:

https://pvpmc.sandia.gov/applications/pv_lib-toolbox/
http://www.sunearthtools.com/dp/tools/pos_sun.php?lang=de



- Estimate of sunlight hours:, i.e. sunrise to sunset

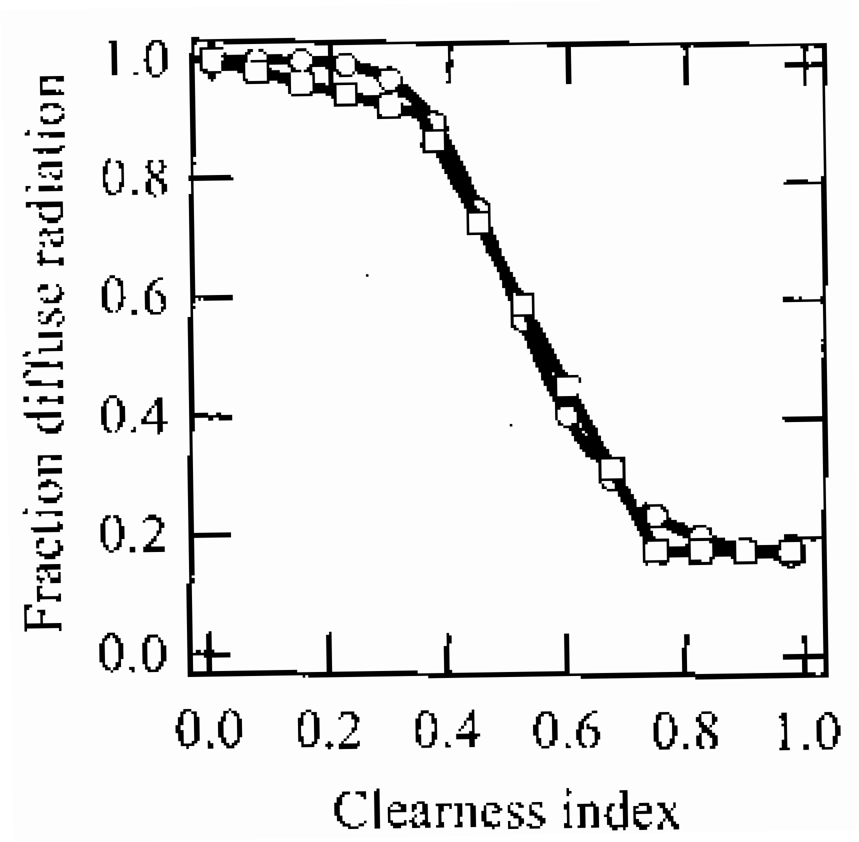
$$N_h = 2\frac{1}{15}\cos^{-1}(-\tan(\phi)\cdot\tan(\delta_s))$$

Solar energy / Solar characteristics

- Models to estimate diffuse fraction:
  - Use clearness index:

$$K_T = \frac{P_D(\beta = 0°)}{\dot{q}_{solar}\cos(\theta)}$$

P_D=Irradiation usable by device
β=tilt ange
q_{solar}=extraterrestrial beam radiation (~1360W/m^2)
D=diffuse irradiation
K_T=clearness index



  - Diffuse fraction:

$$\frac{D(\beta = 0°)}{P_D(\beta = 0°)} = \frac{0.85}{1+50K_T^6} + 0.15$$

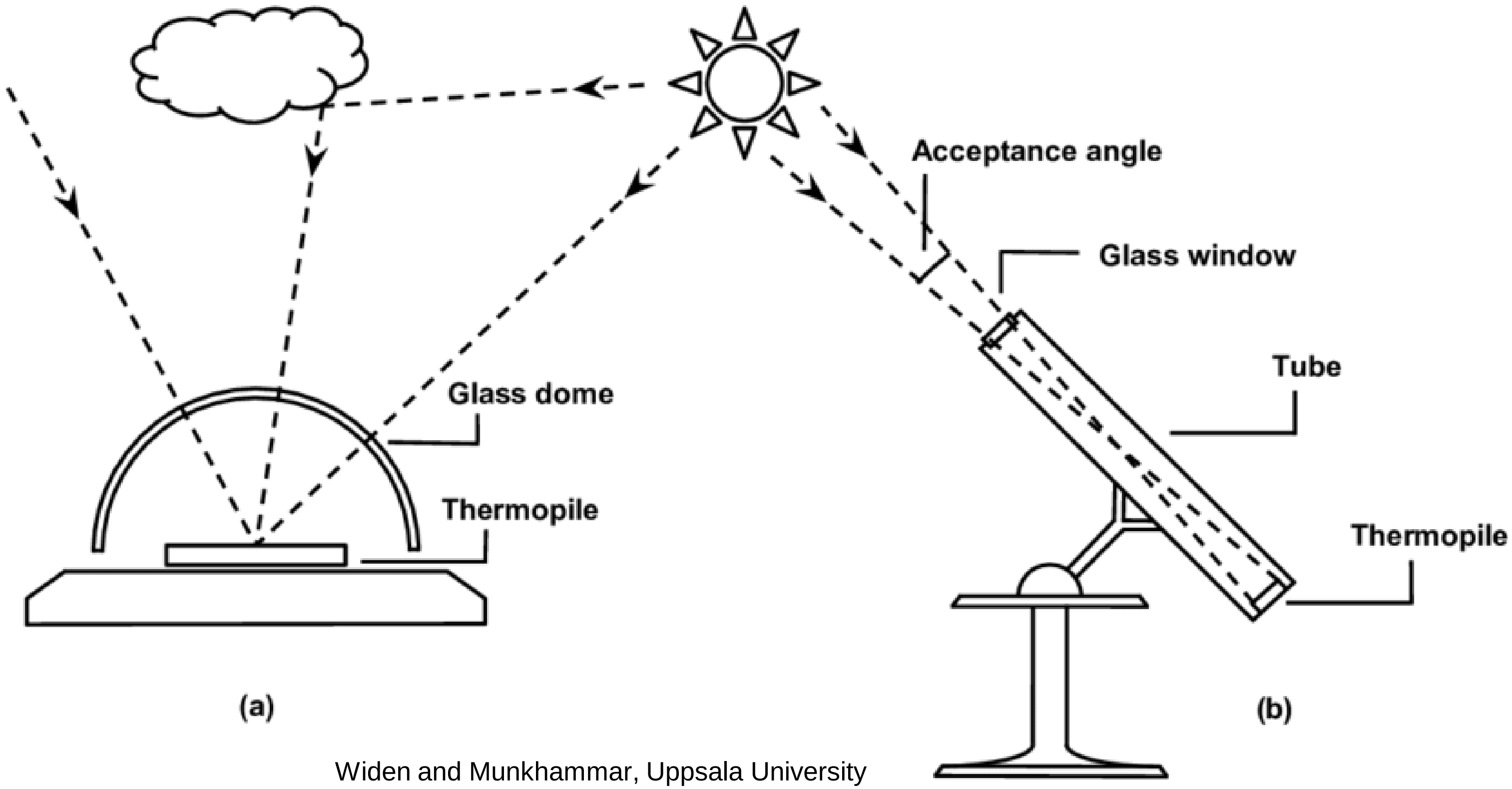
$$\frac{D(\beta = 0°)}{P_D(\beta = 0°)} = \begin{cases} 1-0.249K_T & \text{if } 0 \le K_T < 0.35 \\ 1.557-1.84K_T & \text{if } 0.35 \le K_T < 0.75 \\ 0.1777 & \text{if } 0.75 \le K_T \le 0.35 \end{cases}$$

Solar energy / Solar characteristics

- Exercise 1: Determine the DHI and DNI today in Lausanne, assuming the transmittance of the atmosphere is 60%.

Solar energy / Solar characteristics

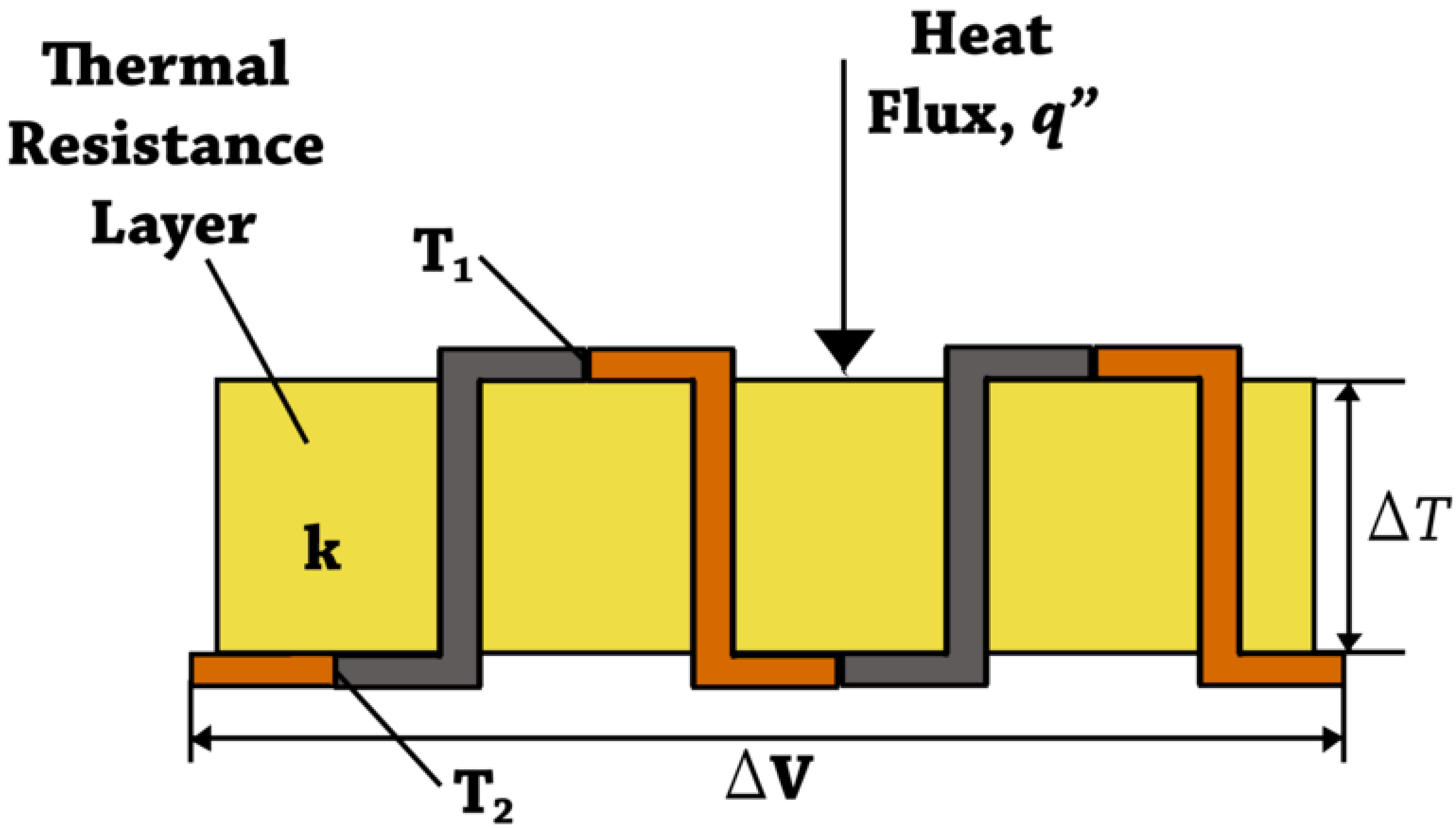
- How to measure
  - DNI: Pyrheliometer installed on sun tracker (b)
  - DHI, GHI: Pyranometer (a), for DHI with shading ring, for GHI horizontally mounted



Widen and Munkhammar, Uppsala University

Solar energy / Solar characteristics

- Thermopile



- Seebeck effect plus Fourier: $\Delta V \rightarrow \Delta T \rightarrow \dot{q}$

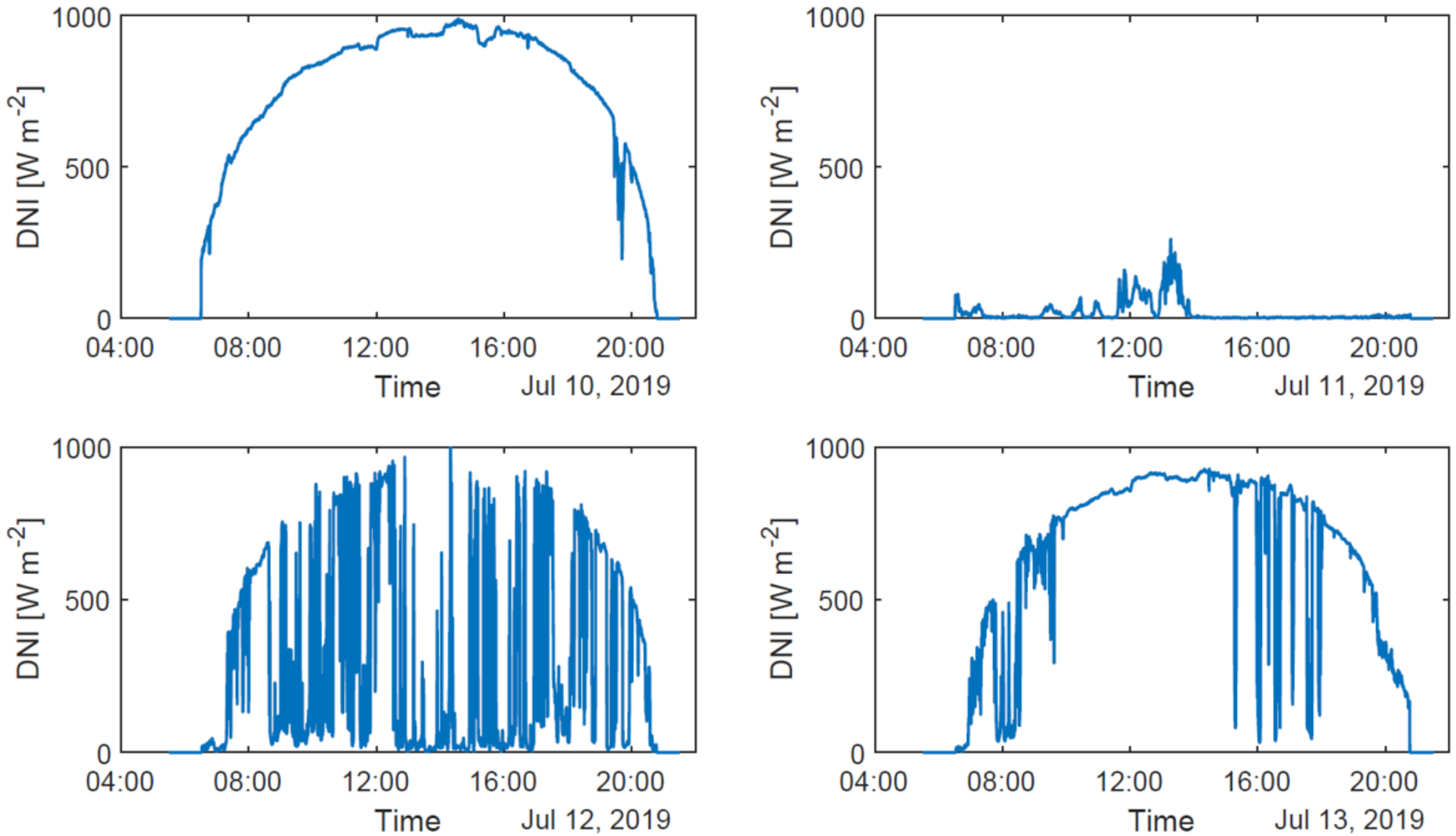
Solar energy / Solar characteristics

- How to measure – NREL's sun station

Solar energy / Solar characteristics

- GHI and DHI measurements at EPFL:

https://www.youtube.com/watch?time_continue=98&v=IZArocR0jps&feature=emb_logo



$$DNI = \frac{GHI - DHI}{\cos(\theta)}$$

Solar energy / Solar potential

- Switzerland:

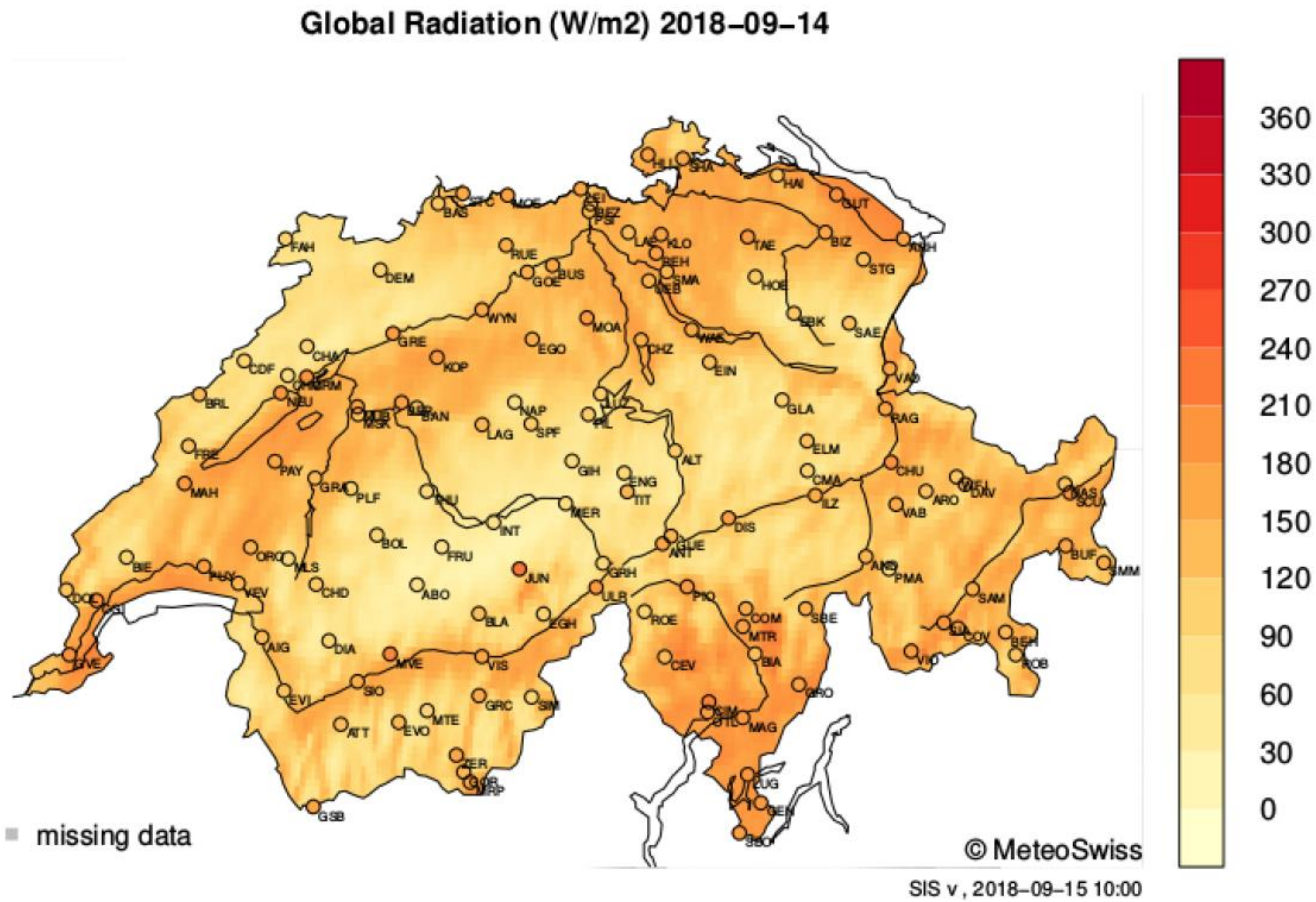


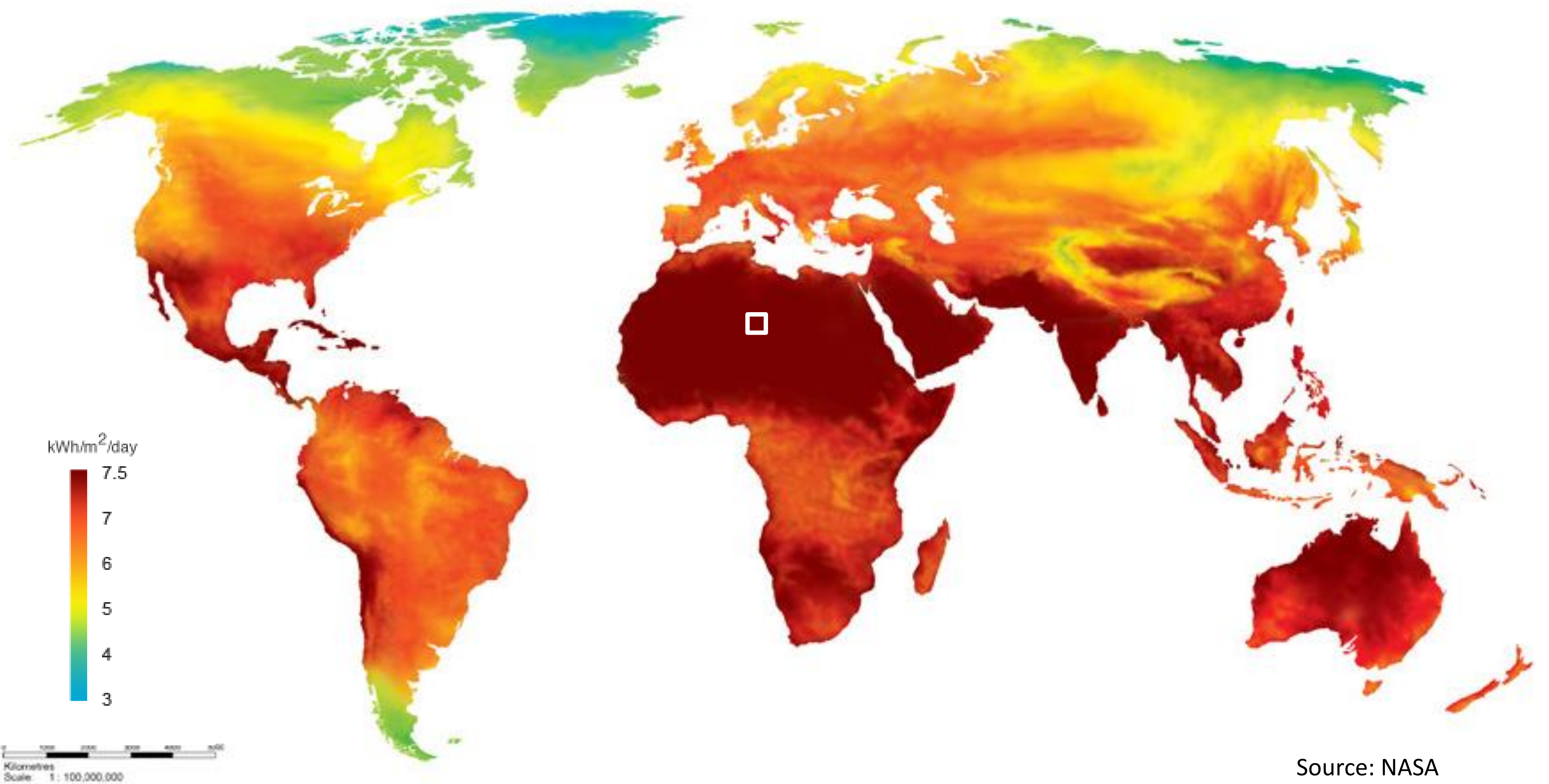
Figure 1: Daily Global Radiation over Switzerland from 14 September 2018.

- What is the potential and what is realistic?

Solar energy / Solar potential

- Solar irradiation:

- Earth's ultimate recoverable oil resource delivered in 1.5 days
- Global annual energy need delivered in 1 hour
- 0.1% of earth surface covered (20% efficient) delivers global annual energy



Source: NASA

Solar energy / Solar potential

[1] International Energy Agency, Statistics, 2012
[2] Lewis, MRS Bulletin, 2007

- Potential of solar energy[1,2]:
  - Global primary energy consumption rate 17 TW
  - Of which 87% non-renewable (fossil, nuclear)
  - Additional supply of renewable in the future 10-20 TW

	Potential (only land)	**Based on:**	**Practical, Economical?**
Solar	36000 TW	Annual average irradiation	500 TW
Wind	50 TW	Annual average wind speed	2 TW
Geothermal	9 TW	Average heat flux at earth surface	1 TW
Hydro	5 TW	Earth topology and water flow	2 TW
Biomass	108 TW	Annual average plant efficiency	7 TW

  - Solar radiation is the indirect source for other renewables

Introduction

- Solar conversion approaches

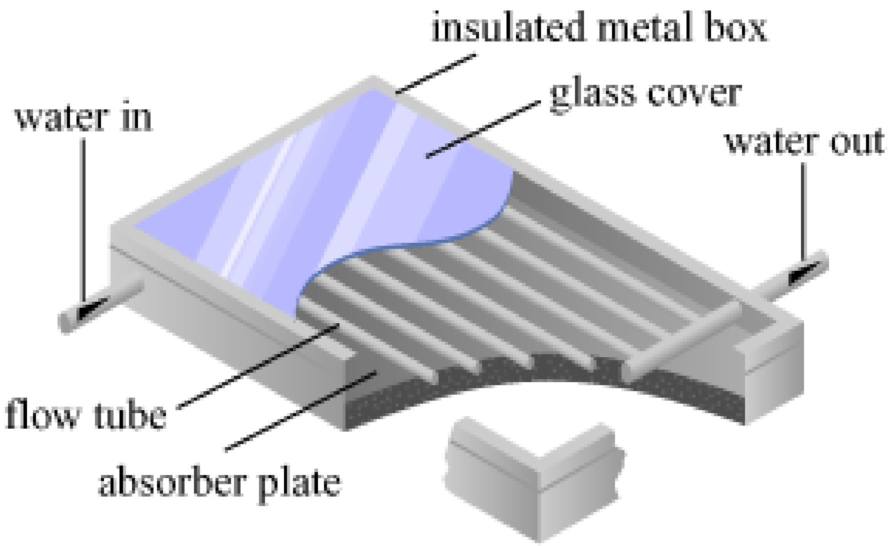
Outline

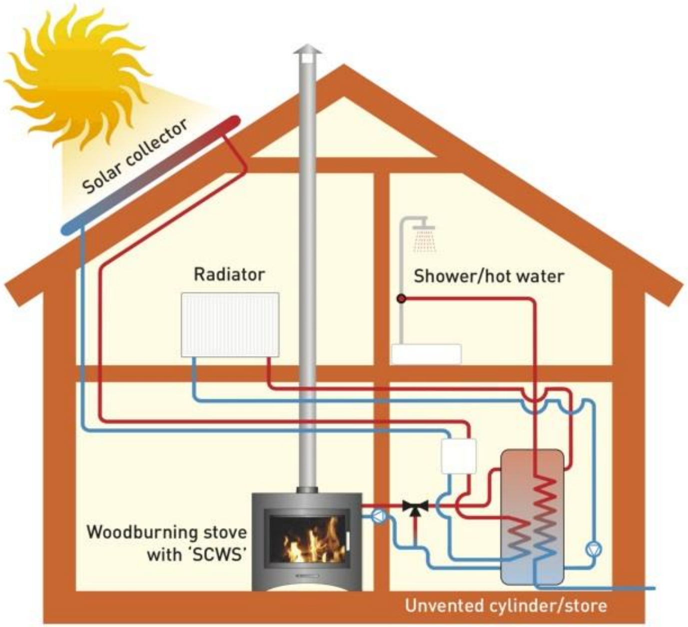
- Overview over use of solar energy
  - Heat
    - Solar collectors
    - Concentrated solar
    - Storage: salinity ponds
  - Electricity:
    - PV
    - CSP
    - Thermoelectrics
  - Heat and electricity:
    - Thermal photovoltaics
    - Co-generation plants
  - Cooling
  - Fuel
    - Thermochemistry
    - Photoelectrochemistry
    - Photobioreactors
  - Treatment of water:
    - Desalination
    - Decontamination

Solar heat

Solar conversion - Heat

- Solar collectors





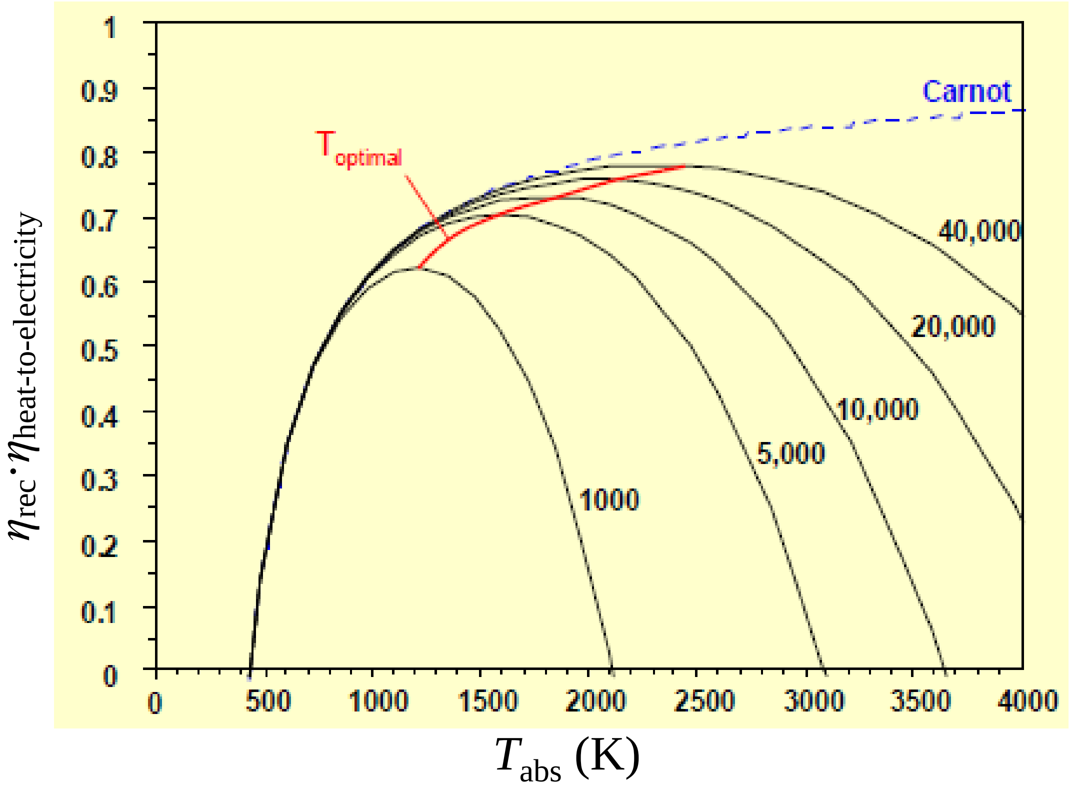
- Black absorber plate and heat transfer fluid
- Temperatures up to 200°C (dependent on technology and heat transfer design)
- Efficiencies in the range of 70%:

$$q_c = A_c F'\left(q_{\text{sol,in}}''\eta_{\text{opt}} - U_L(T_{\text{cm}} - T_a)\right) = mc_p(T_{\text{co}} - T_{\text{ci}})$$

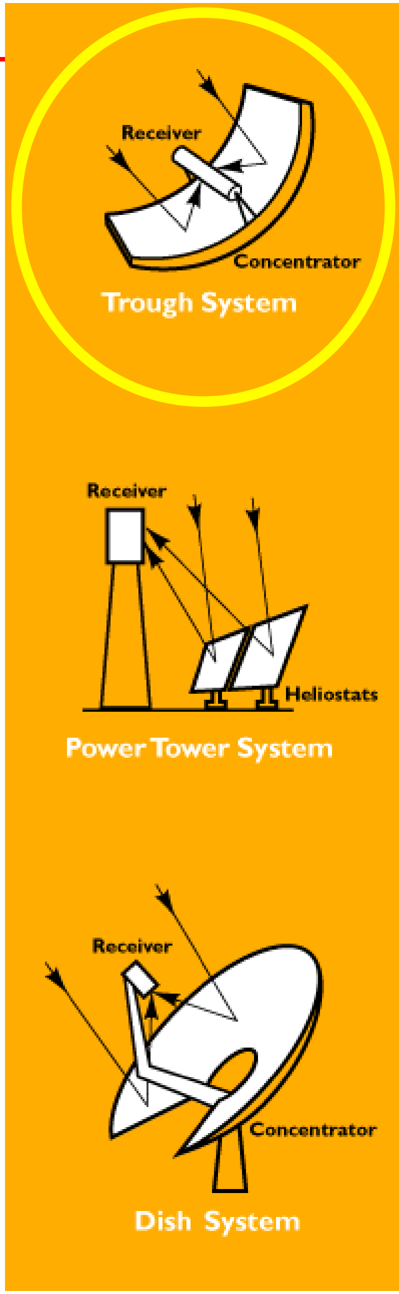
- Industrial and residential applications

Solar conversion - Heat

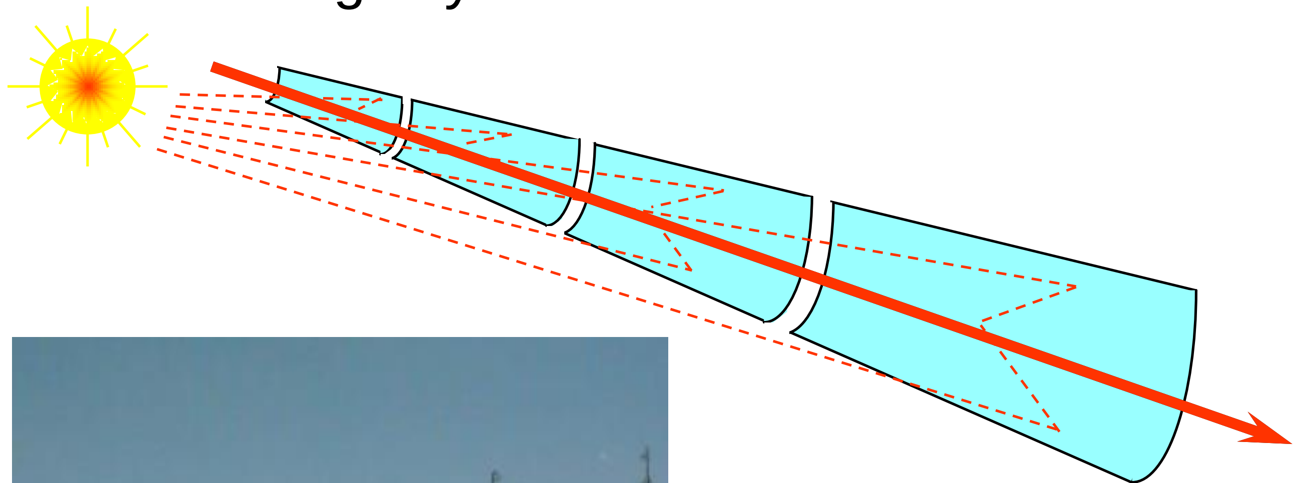
- Concentrated solar:
  - Needs direct radiation so as to be able to concentrate
  - Allows for higher temperature and efficiencies



Solar conversion - Heat



Parabolic trough system:



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

Solar conversion - Heat

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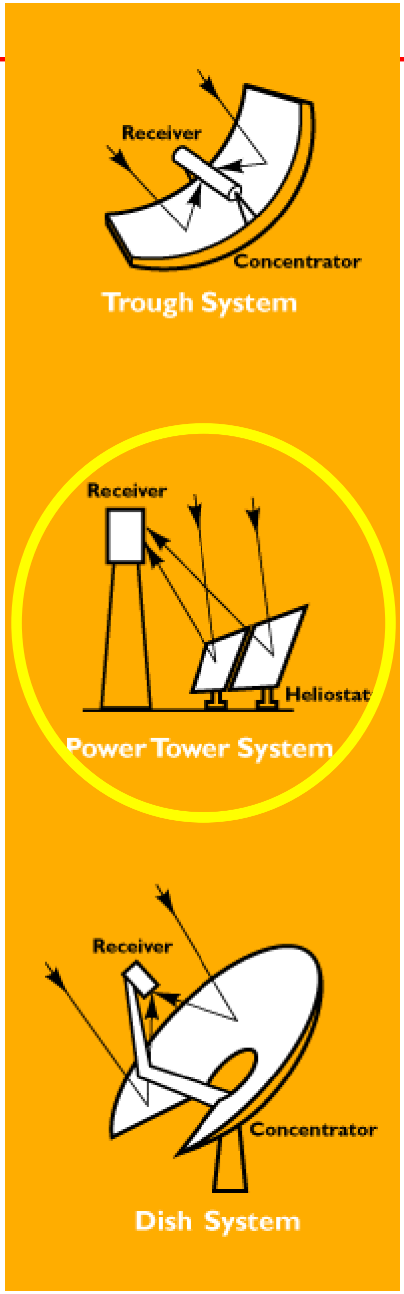
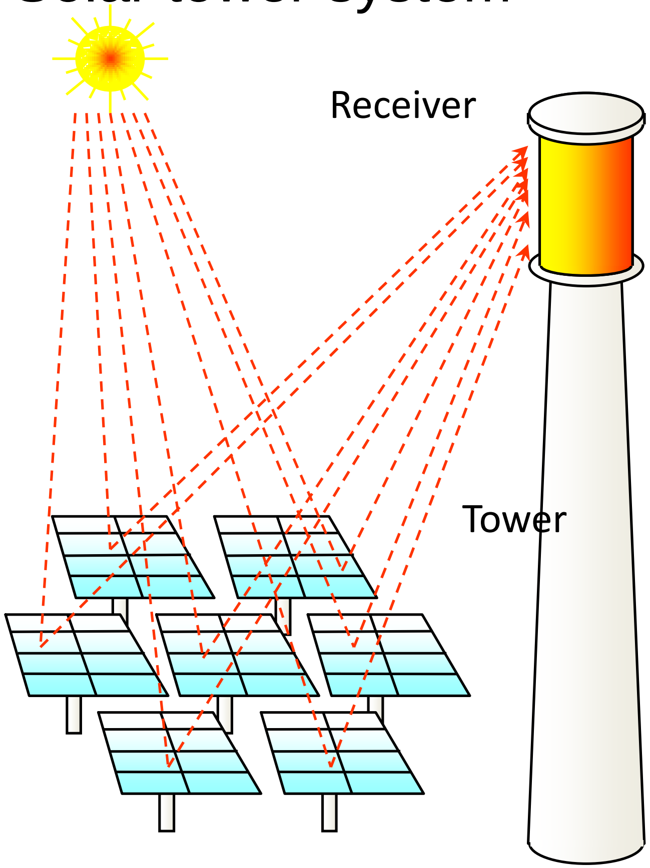
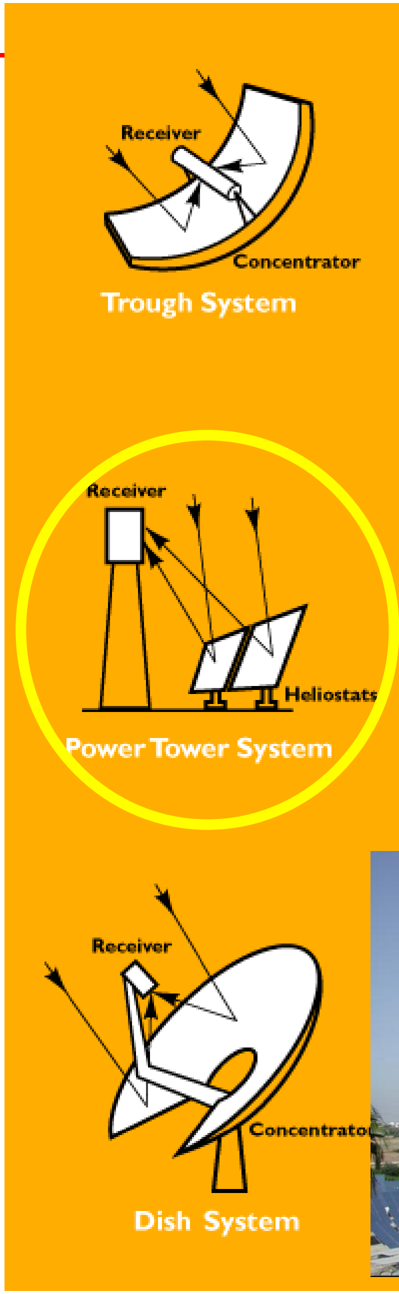


Solar tower system

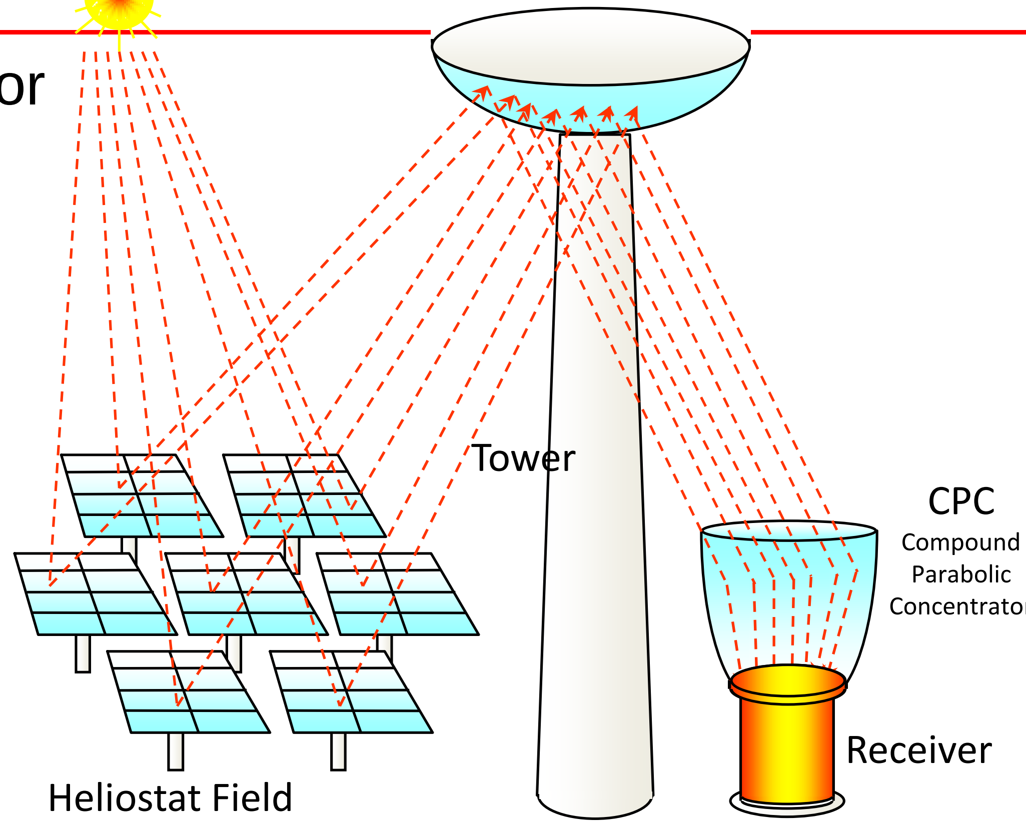


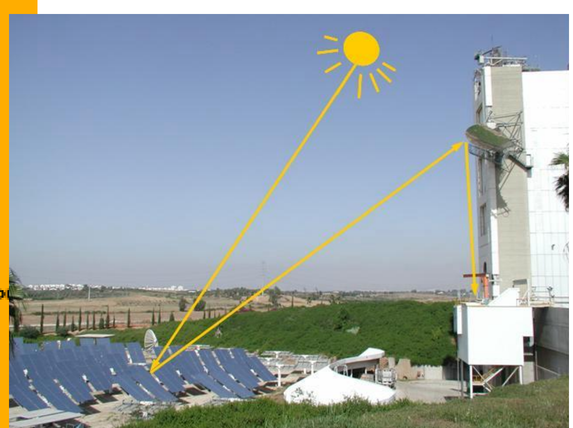
- Point focusing.
- C = 200 - 1000.
- Unit 30 - 200 MW.
- 2-axis tracking heliostats: elements o different parabolas with varying focal length.

Solar conversion - Heat

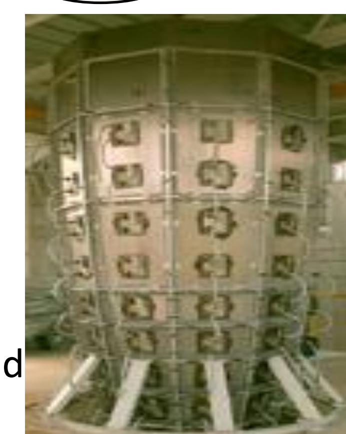


- Tower reflector





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



Solar conversion - Heat

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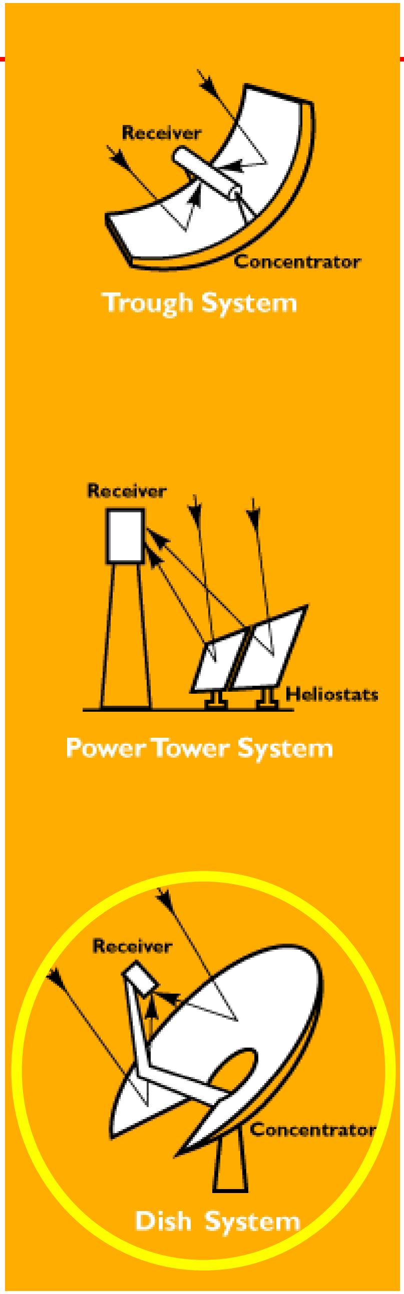
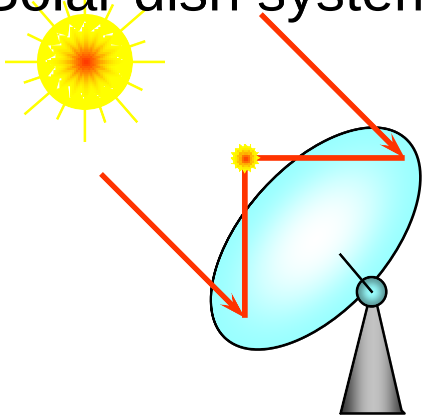


Solar dish system



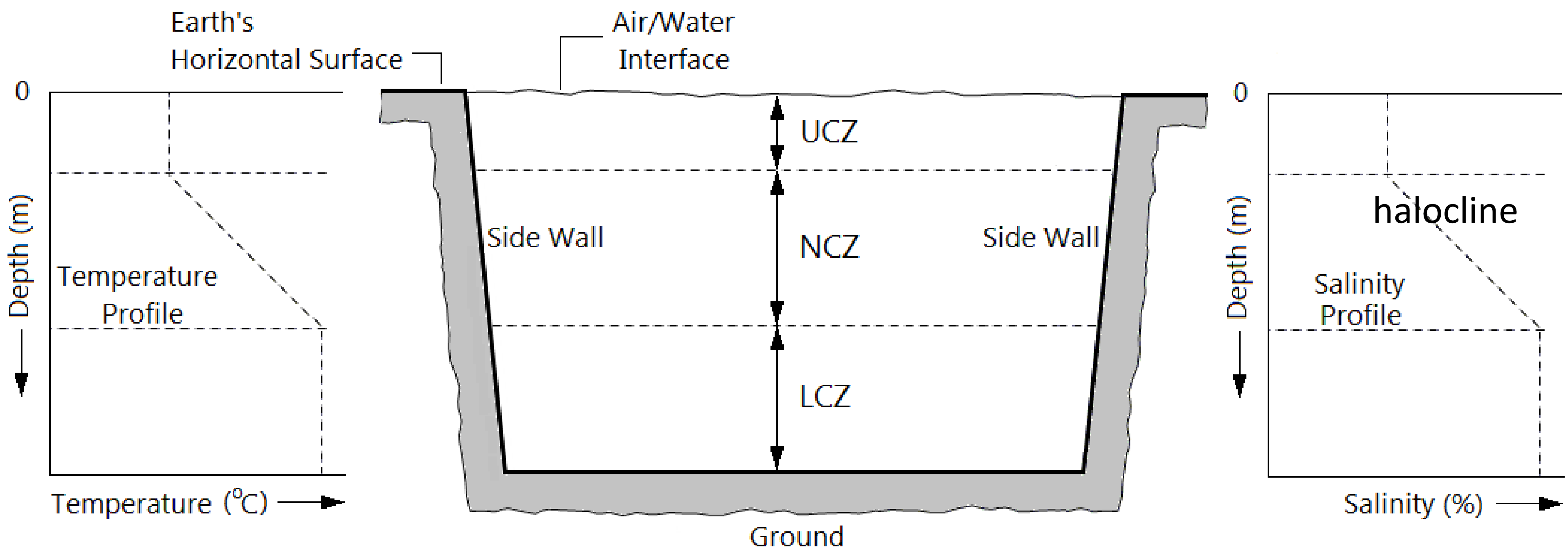
- Point focusing.
- C = 1000 - 13,000.
- Unit 7.5 - 100 kW.
- 2-axis tracking parabolic dish.
- Modularity.
- Remote applications.

EPFL’s solar dish

Solar conversion - Heat

- Salinity gradient pond - Working principle

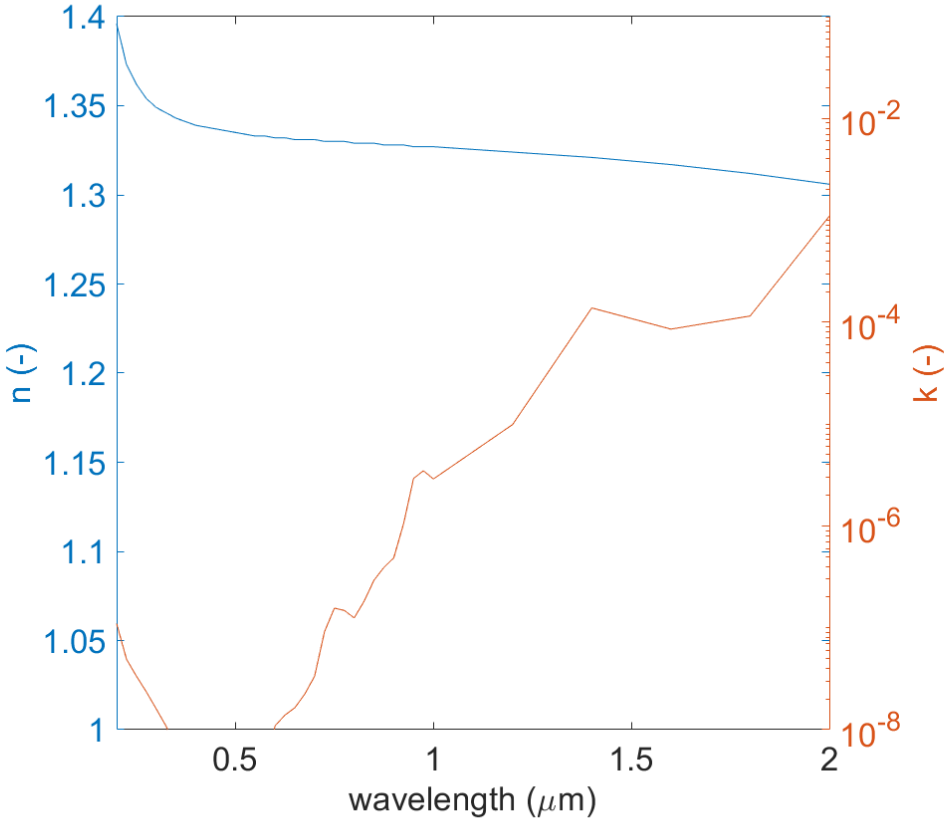
UCZ: upper convective zone
NCZ: non-convective zone
LCZ: lower convective zone

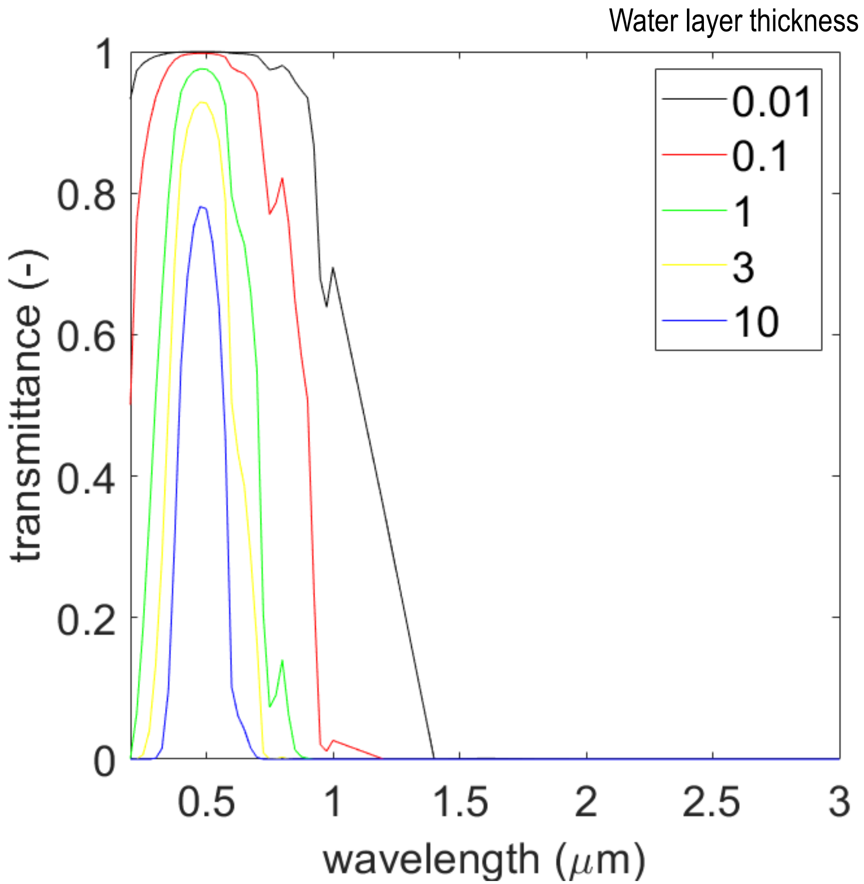


  – Typical depth ~3m

Solar conversion - Heat

- Salinity gradient pond - Refractive index of water, water absorption





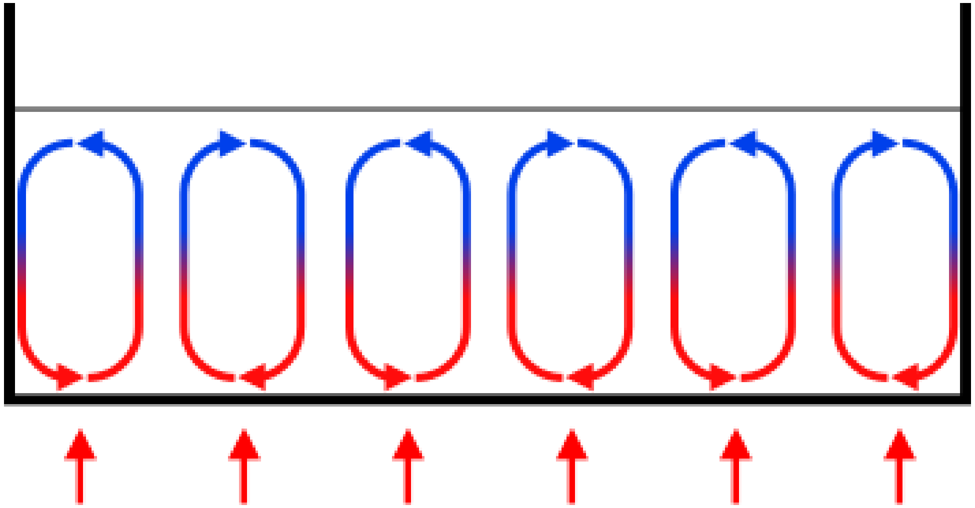
Solar conversion - Heat

- Salinity gradient pond: Without presence of salinity gradient: Rayleigh–Bénard convection

$$\rho\mathbf{u}\cdot\nabla\mathbf{u} = -\nabla p + \nabla\mu\nabla\mathbf{u} + \rho\beta(T - T_0)g$$

$$\nabla\mathbf{u} = 0$$

$$\mathbf{u}\cdot\nabla T = \nabla\cdot\alpha\nabla T$$

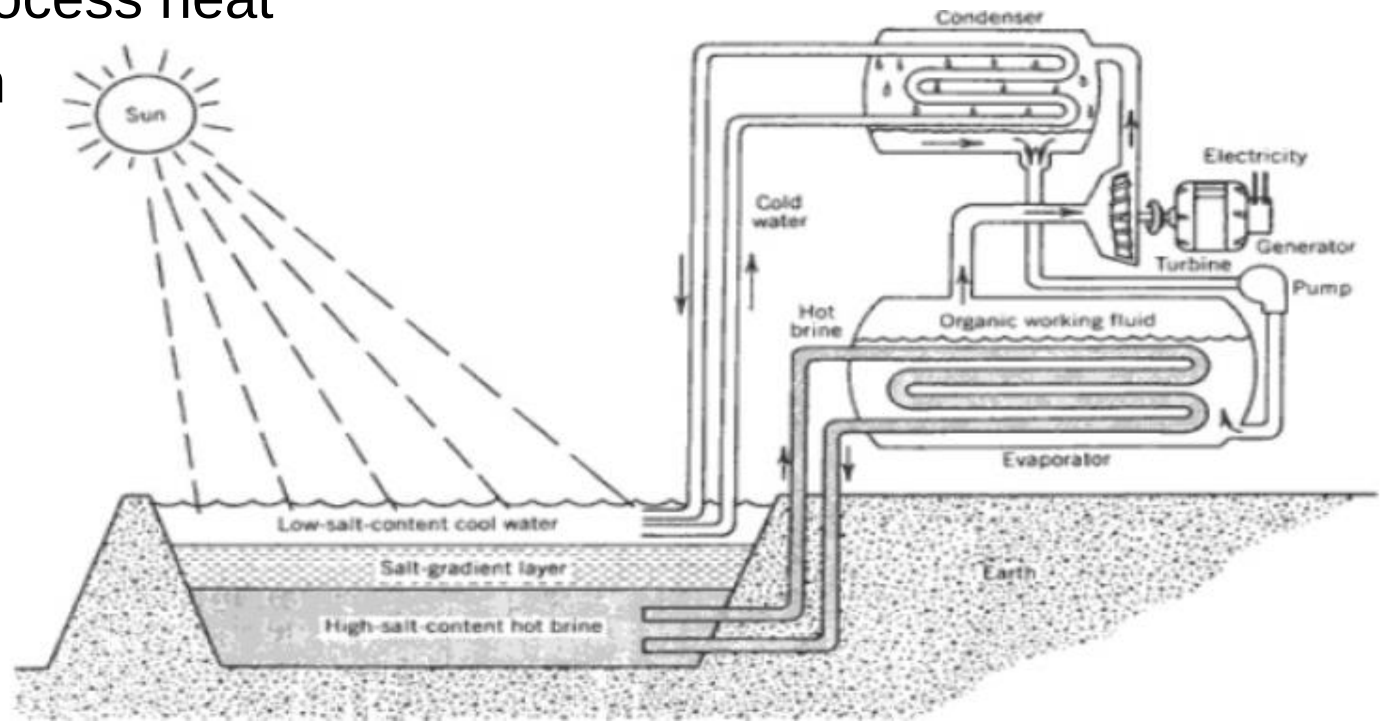


$$\mathrm{Ra}_L = \frac{g\beta}{\nu\alpha}\left(T_b - T_t\right)L^3$$

T_t: temperature of the top plate
T_b: temperature of the bottom plate
L: height of the container
g: acceleration due to gravity
v: kinematic viscosity
α: thermal diffusivity
β: thermal expansion coefficient

Solar conversion - Heat

- Salinity suppresses convection
- Heat can only be lost due to conduction towards top layer
- Allows for storing thermal energy (temperatures limited to <90°C) for applications in:
  - Heating/cooling of buildings
  - Power production
  - Industrial process heat
  - Desalination



Solar conversion - Heat

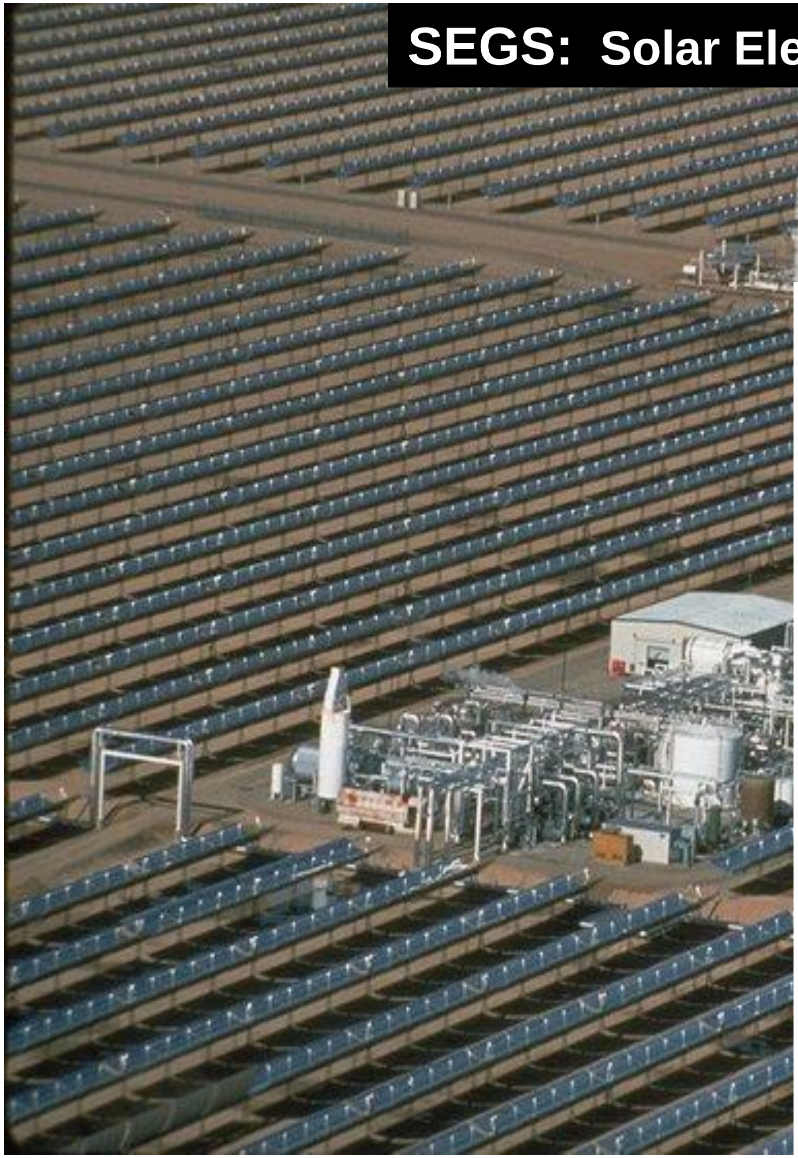
- Three examples of salinity gradient solar ponds:
  - Beit HaArava solar pond — totaling an area of 210'000 m^2 – reported peak output of 5 MW, operated until 1988
  - Gujarat Dairy Development Corporation project in India supplied around 22'000'000 kWh of thermal energy a year to the dairy plant — before the regional dairy collapsed 2001 (Bhuj earthquake)
  - Bruce Foods' solar Pond, totaling 3'200m^2, provides around 20% of the energy to the plant in El Paso.

Solar electricity

Solar conversion - Electricity

- Concentrated solar power

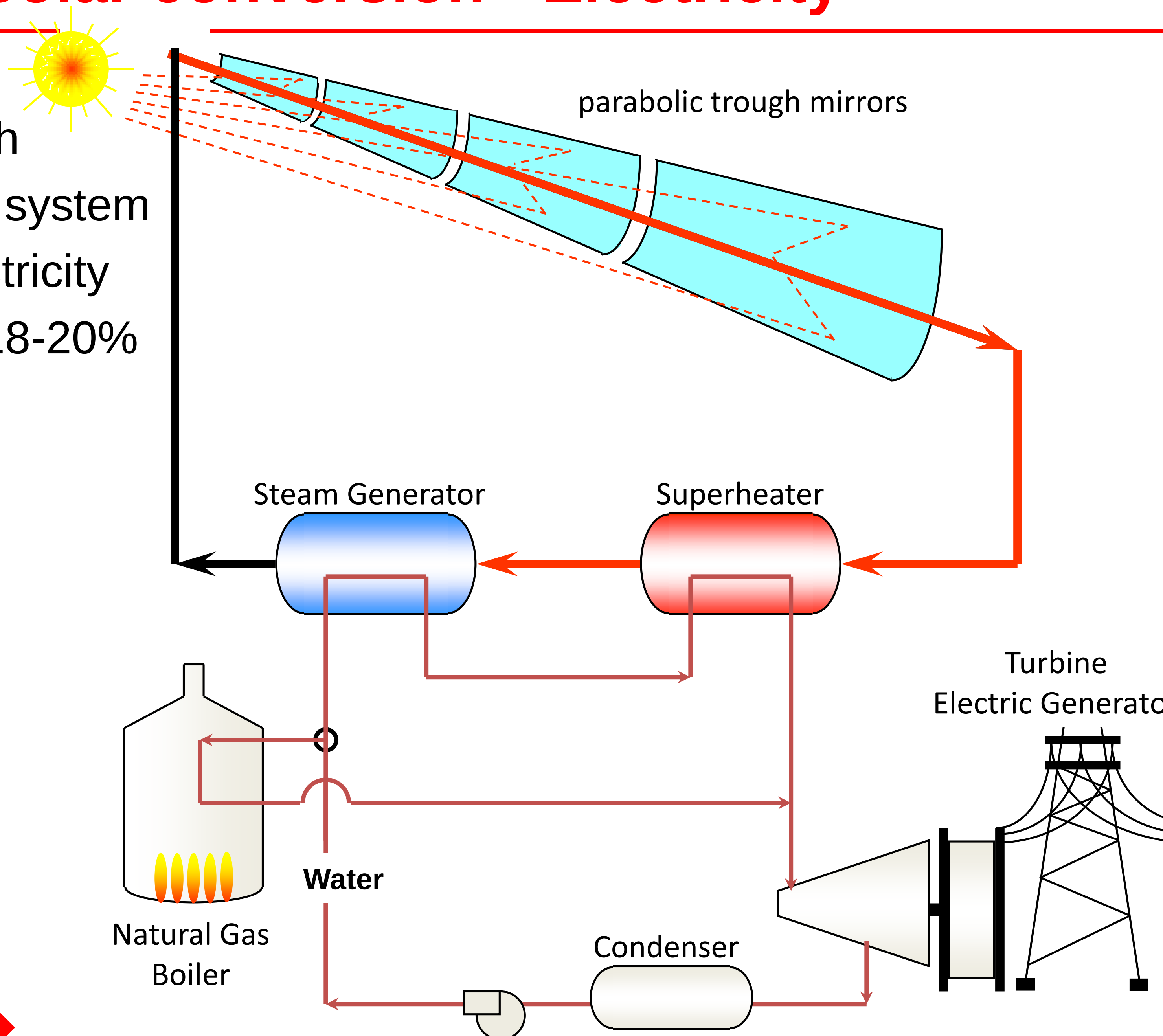
SEGS: Solar Electricity Generation Systems



- 354 MW_e at Mojave Desert
- Annual production: 1100 GWh (approx. 220,000 households)
- In operation: since 1985.
- Operated by Kramer Junction Co.
- 2.5 million m^2 parabolic troughs.
- Synthetic oil as HTF heated to 391°C.
- Thermal energy fed to turbines: 75% solar / 25% NG fired.
- Operational strategy: 55% income for selling 16% of solar electricity at peak hours.
- Mean annual efficiency: 14%

Solar conversion - Electricity

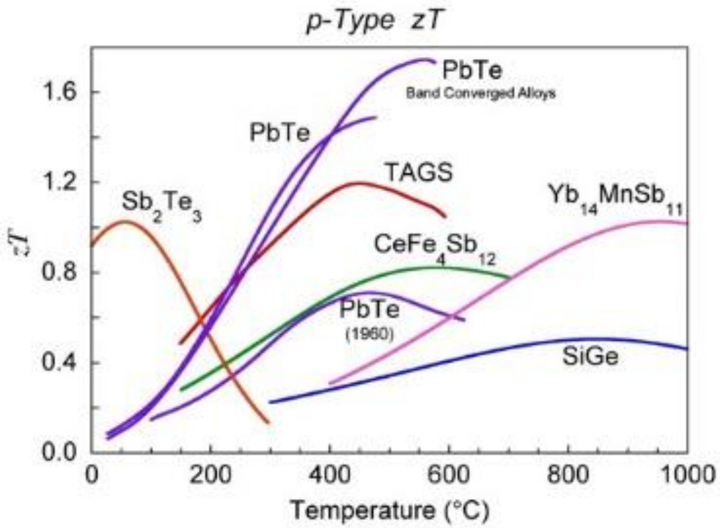
- Based on Parabolic trough
- Here, hybrid system
- Solar-to-electricity efficiency ~18-20%



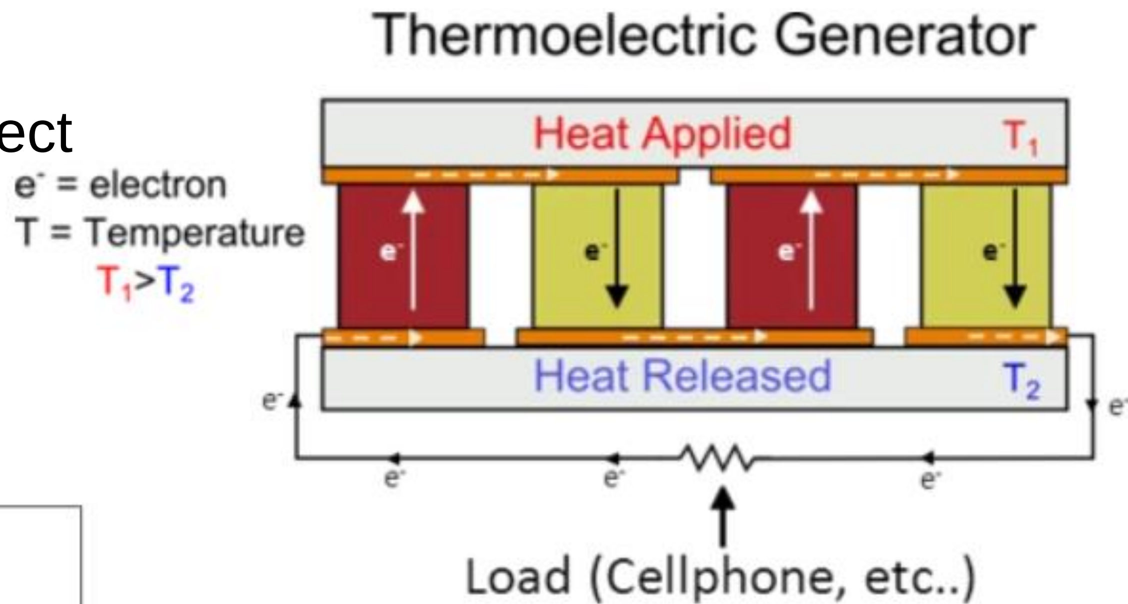
Solar conversion - Electricity

- Thermoelectrics
  - Based on Seebeck effect
  - Figure of merit:

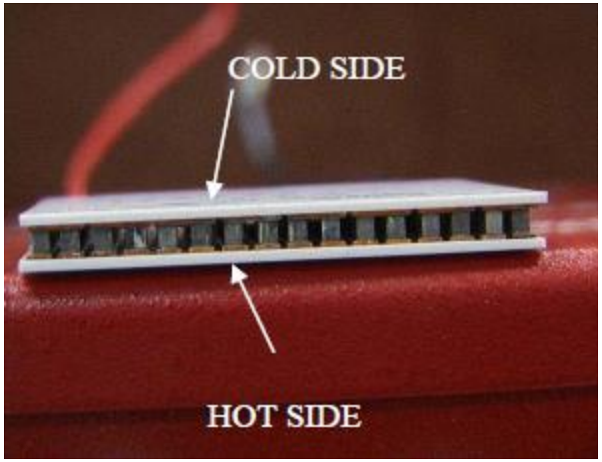
$$zT = \frac{\sigma S^2 T}{\lambda}$$



  - Efficiency (heat to power) ~1-2% for zT ~ 1

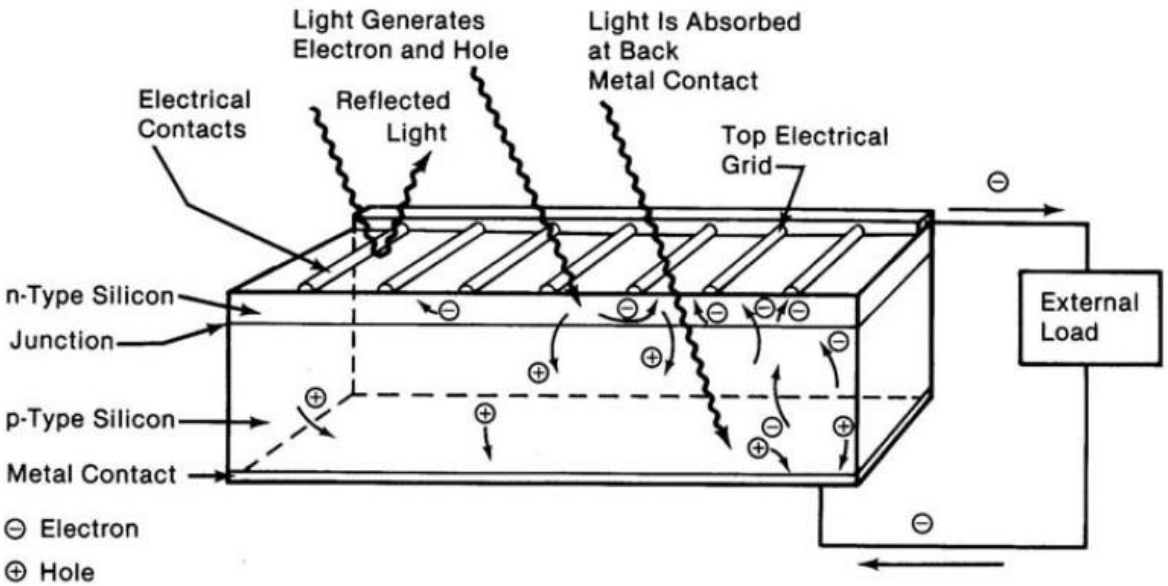


https://powerpractical.com



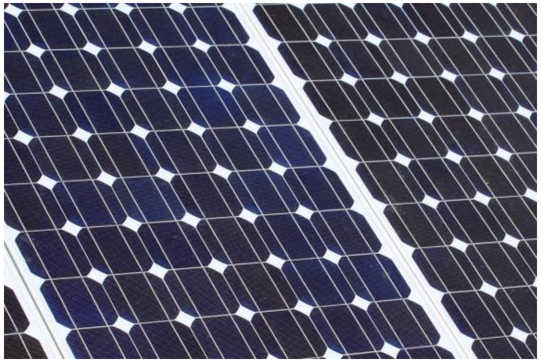
Solar conversion - Electricity

- Photovoltaics



Basic photovoltaic principles and methods, 1981.

  – Market dominated by Si
  – Typical solar-to-electricity efficiency: ~18%-22%

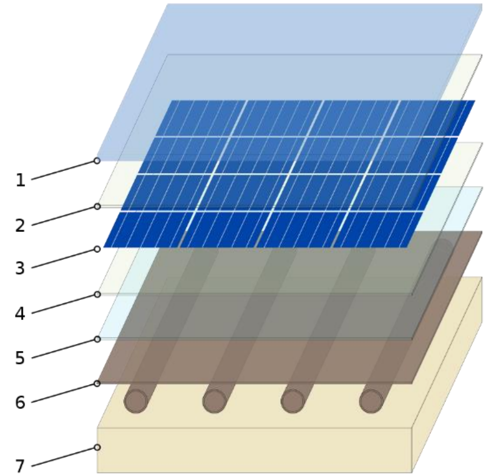


Solar electricity and heat

Photovoltaic thermal modules

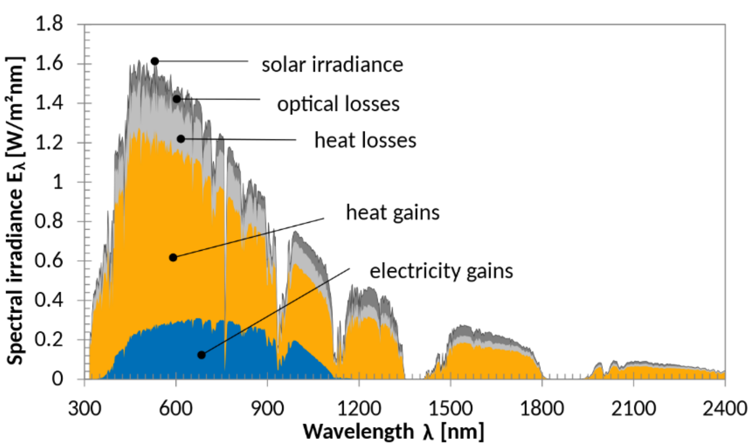
- A mix between photovoltaics and thermal collectors:

1 - Anti-reflective glass
2 - Encapsulant
3 - Solar PV cells
4 - Encapsulant
5 - Backsheet
6 - Heat exchanger
7 - Thermal insulation



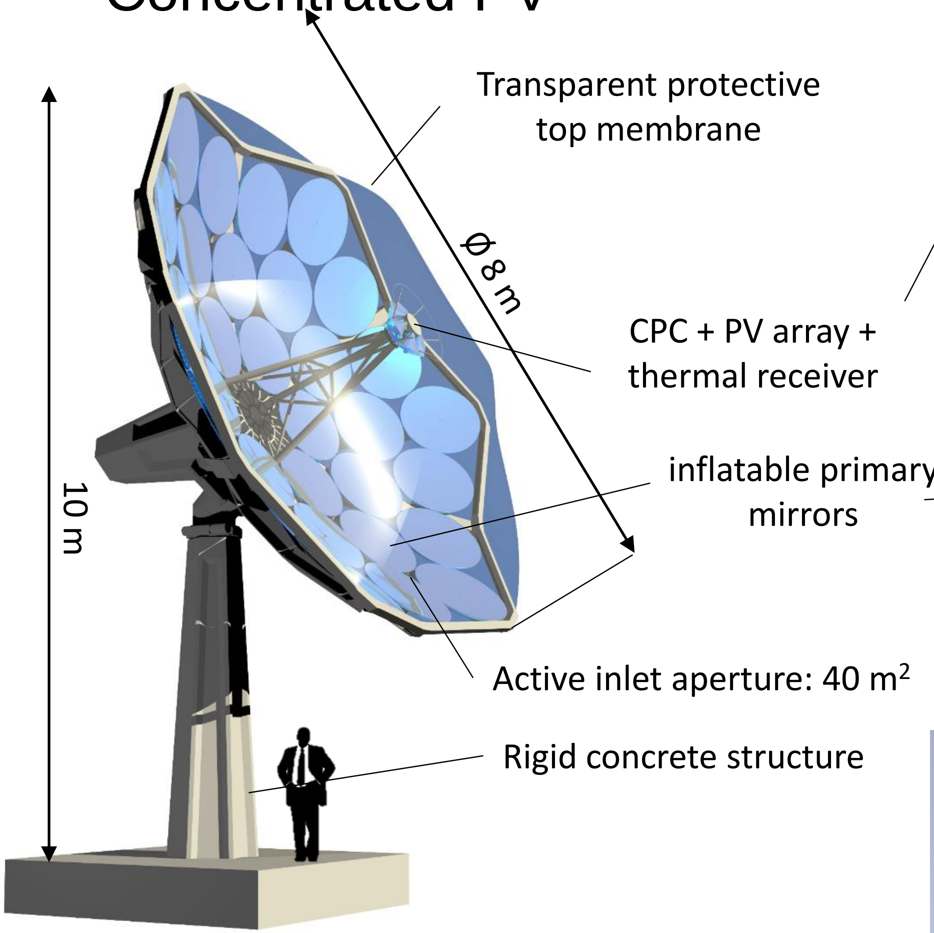
https://en.wikipedia.org/wiki/Photovoltaic_thermal_hybrid_solar_collector

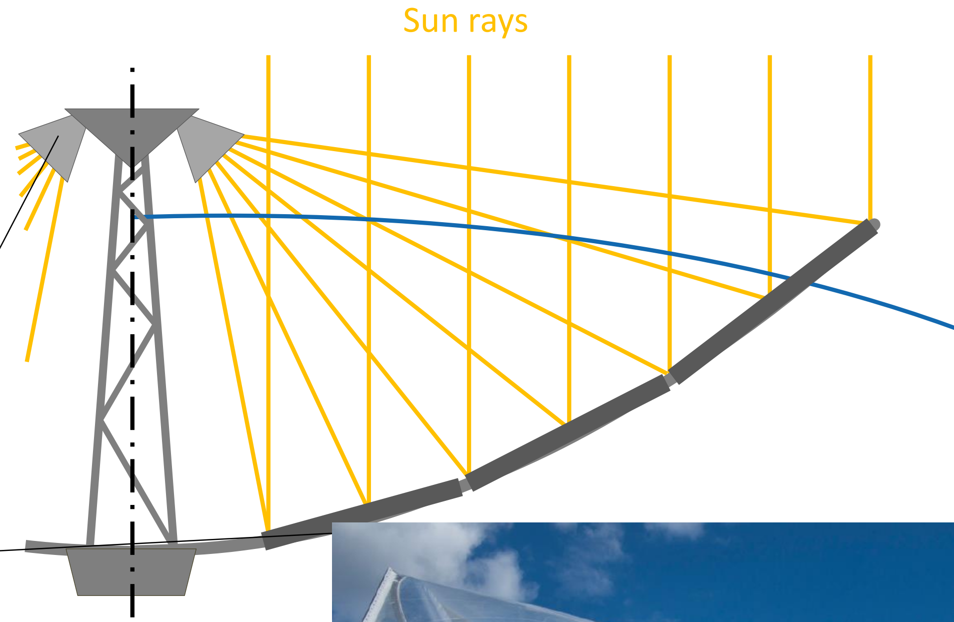
- Rational: Use more of the solar spectrum

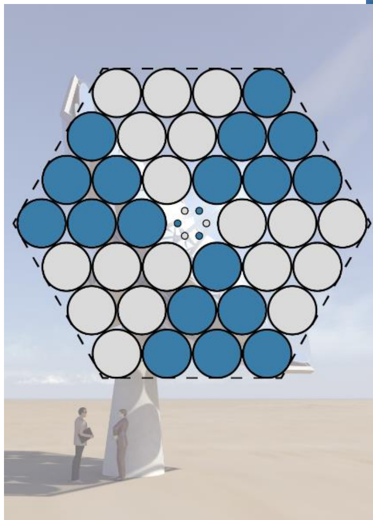


CPVT

- Concentrated PV







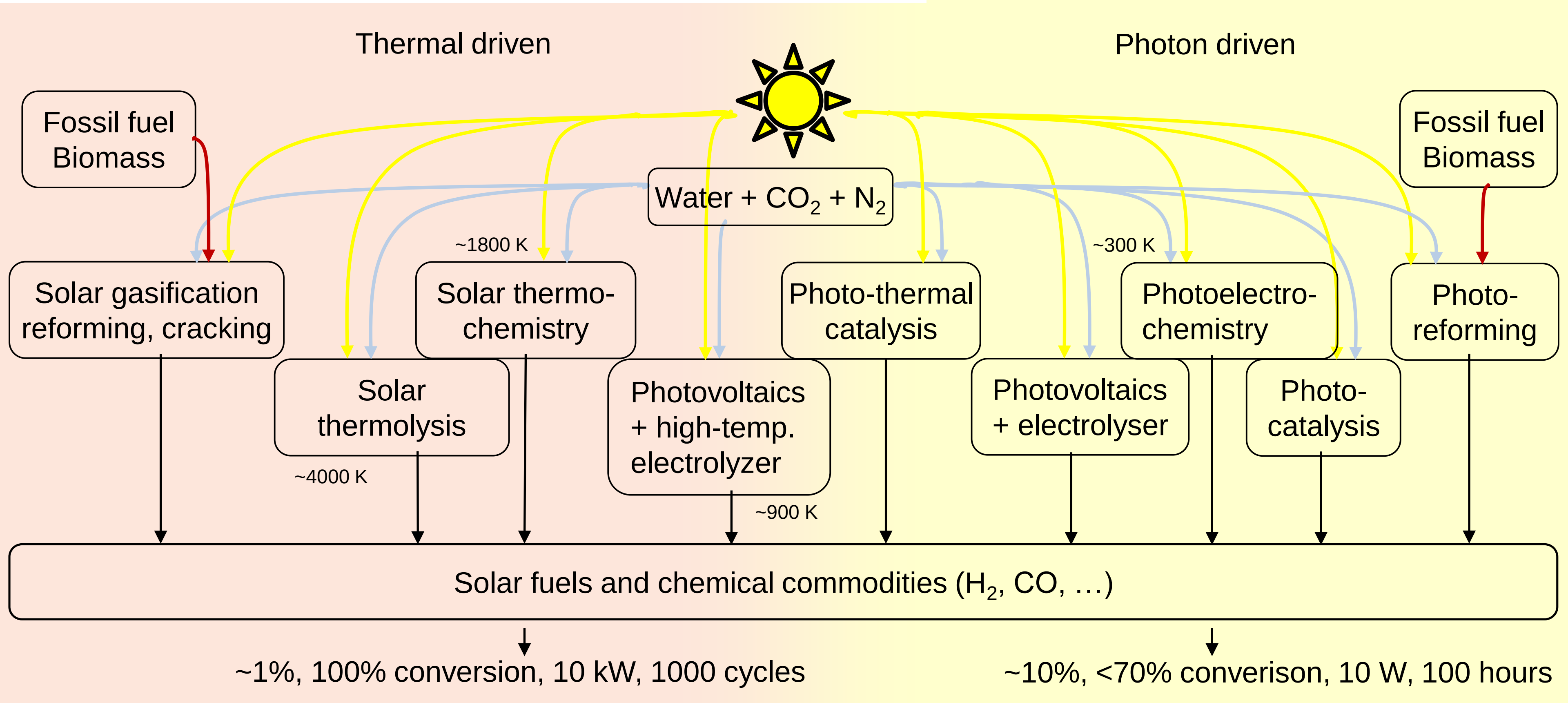
Source: https://prec.ethz.ch/research/solar-power.html

- Size: 12 kW electrical and 21 kW thermal @ 90ºC
- Efficiency: ~30% electrical + ~50% thermal
- Microchannel cooled CPV receiver
- Key Aspects: concrete structure, inflatable mirrors

Solar fuels and materials

Solar fuels (Non-Biological)

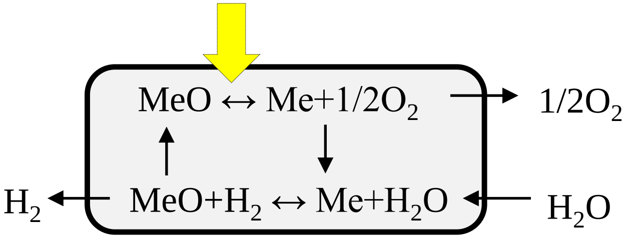
- Thermal and photon-driven, and combinations thereof

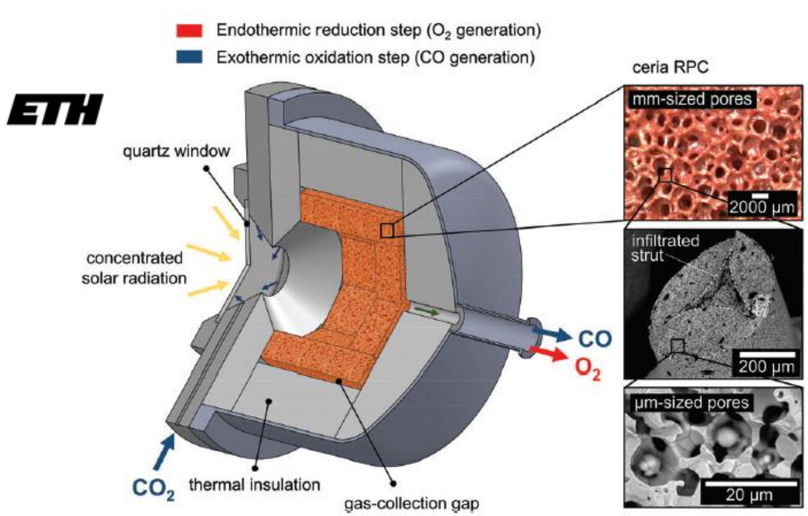


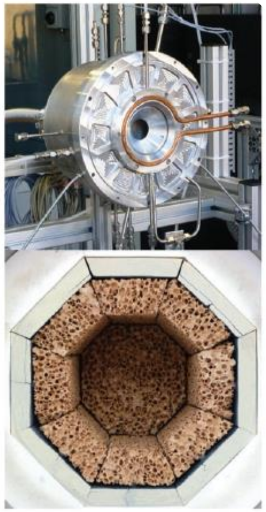
Solar Fuels

- Solar thermochemistry

  Ceria-based cycles
  - Efficiency: 3-5%
  - Scale: kW to 0.1 MW-scale
  - Stability: thousand of cycles





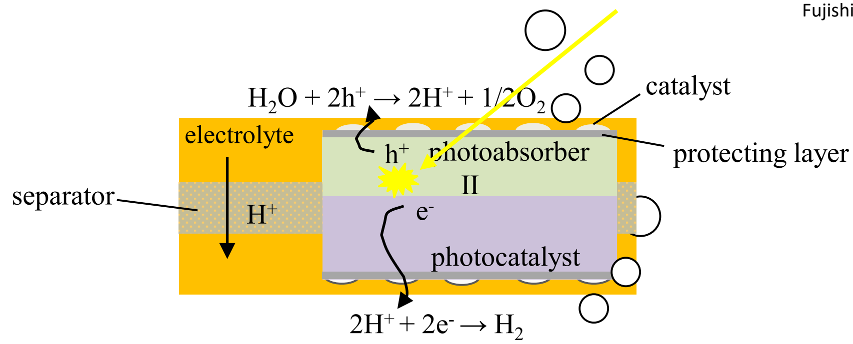


Marxer et al., *Energy Environ Sci*, 10, 2017

Solar fuels

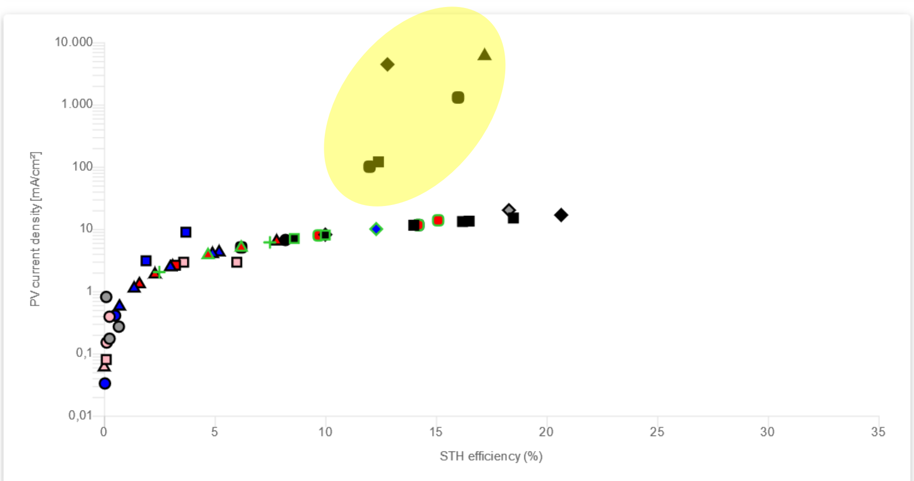
- Photoelectrochemical approaches

Fujishima et al., *Nature*, 238, 1972.



- Use of electron/hole pair directly for reaction

http://specdc.epfl.ch/



LEGEND

Fill color - PV / photoabsorber material	Boundary color - EC material	Symbol shape - PV / photoabsorber and EC configuration	
All III-V	Rare metal-based (expensive)	O 2J, integrated PVs and catalyst	+ 3J, integrated PVs and catalyst
Partial III-V	Abundant (cheap)	□ 2J, integrated PVs, wired catalyst	Δ 3J, integrated PVs, wired catalyst
All Si		◇ 2J, non-integrated PVs or catalyst	O 3J, non-integrated PVs or catalyst
Partial Si			
Oxides and others			

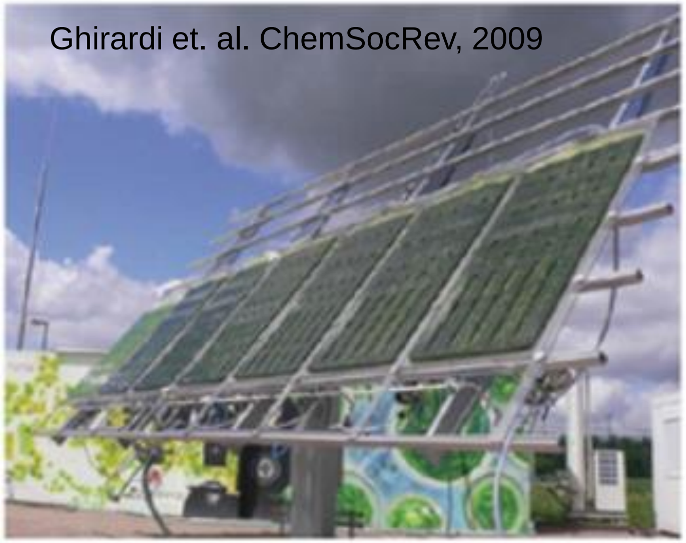
w/o multi-module demonstrations
w/o multiple electrolyzer demonstrations

Solar Fuel Approaches

- Natural photosynthesis or bio-organism

  Annually averaged efficiency
  - Typically <1%
  - Microalgae: 3%

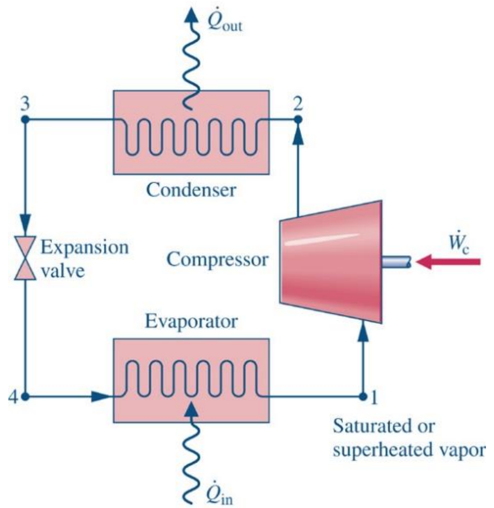
Blankenship et al., *Science*, 332, 2011

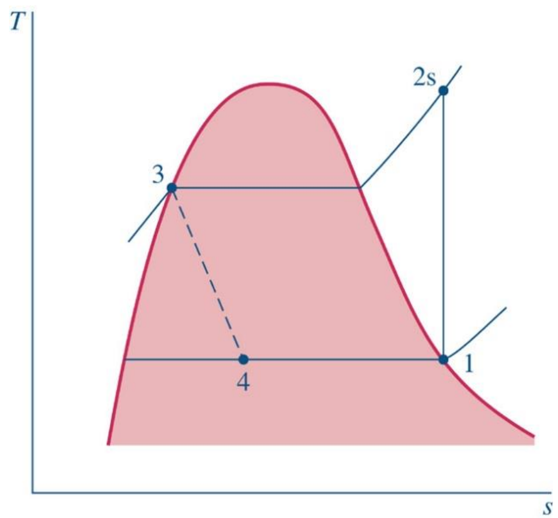


Solar cooling

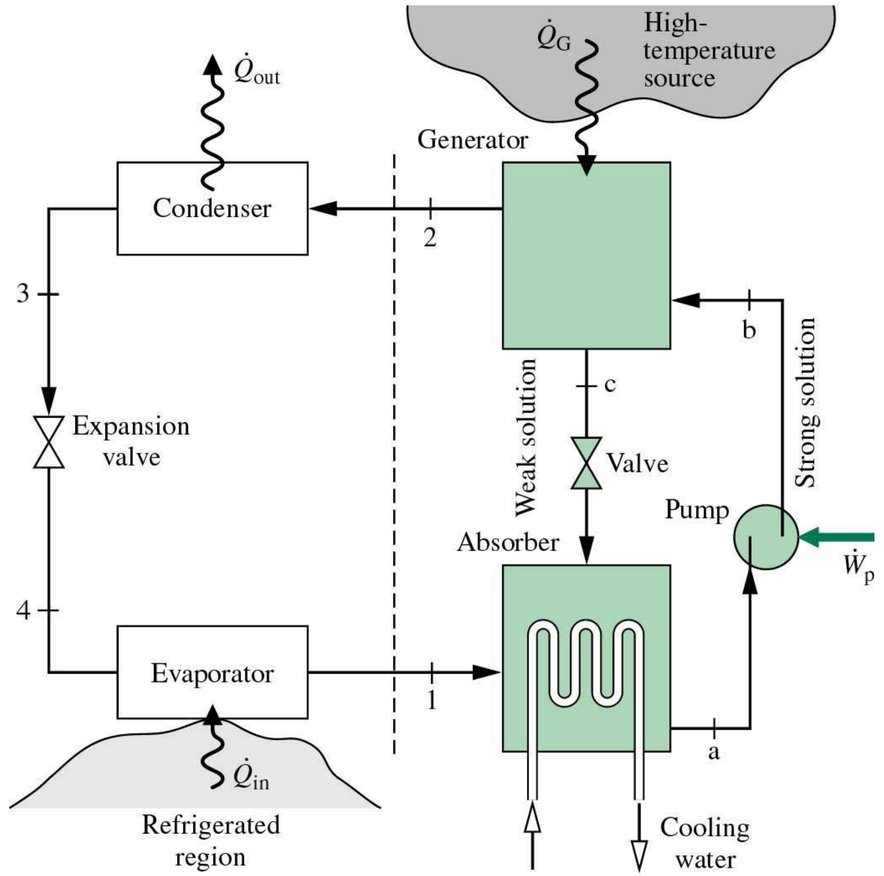
Solar airconditioning

- PV-based vapor compression refrigeration cycle





Absorption cooling

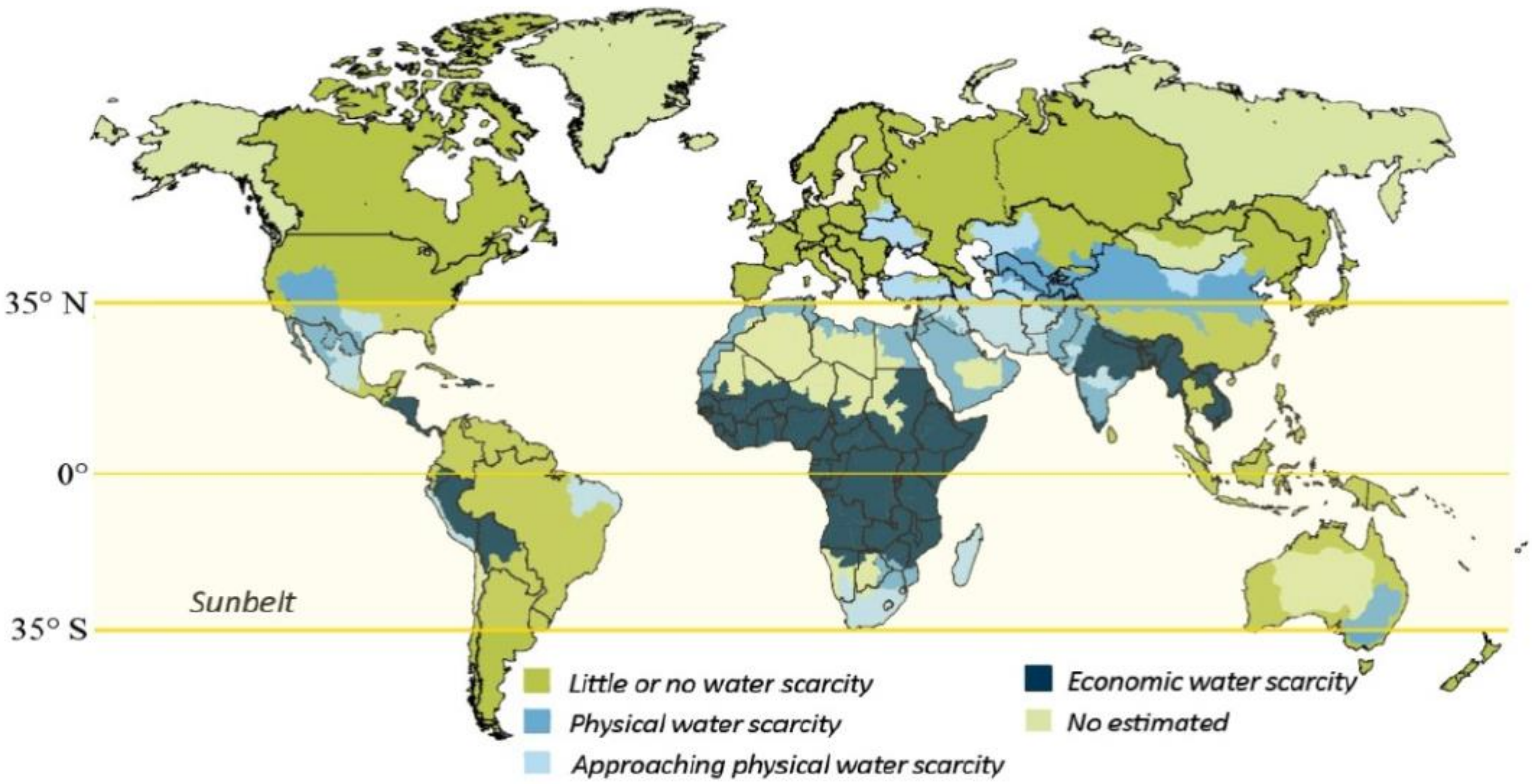


e.g. using ammonia as refrigerant and water as absorbent
Or water as refrigerant and lithium bromide as absorbent

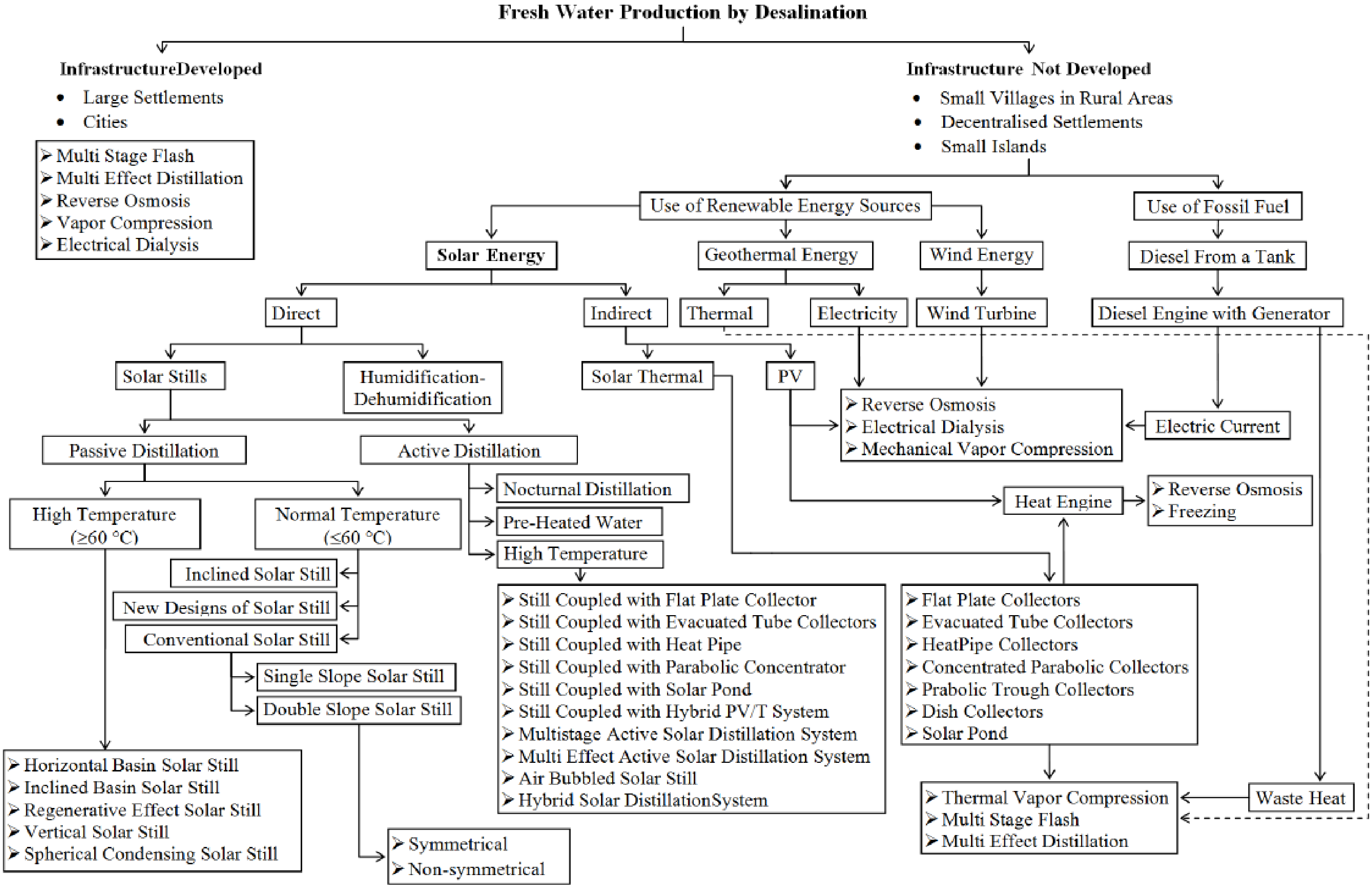
Solar water treatment

Water-Energy-Nexus

- Water scarcity in areas with typically large solar energy potential

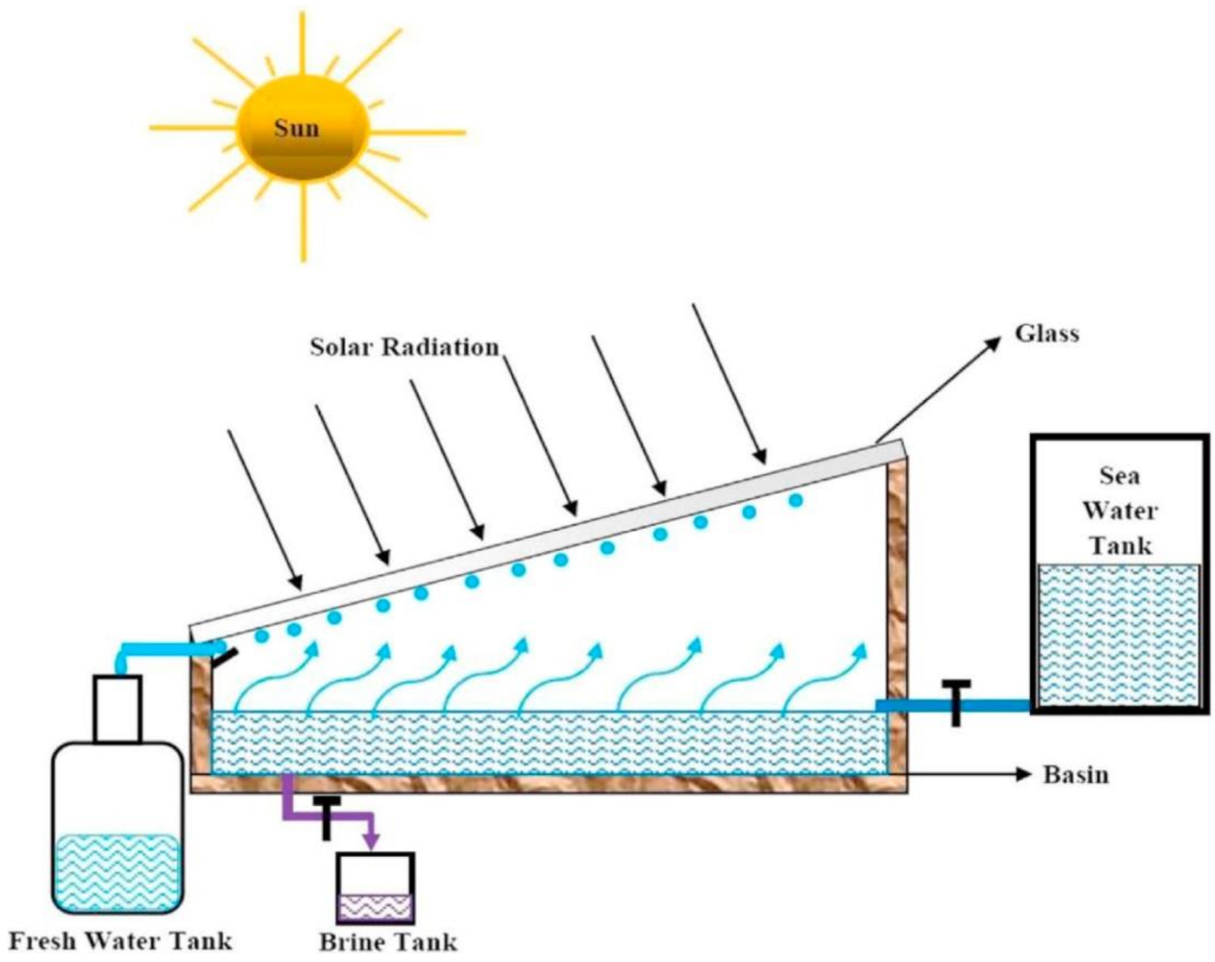


Water desalination



Solar still

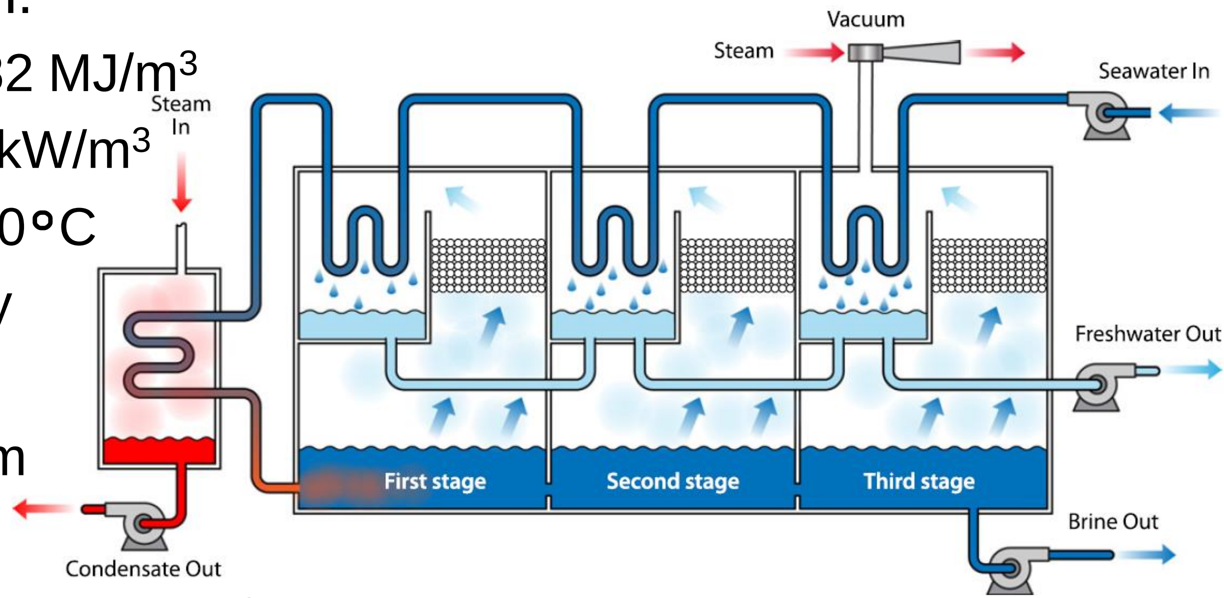
- Active and passive stills



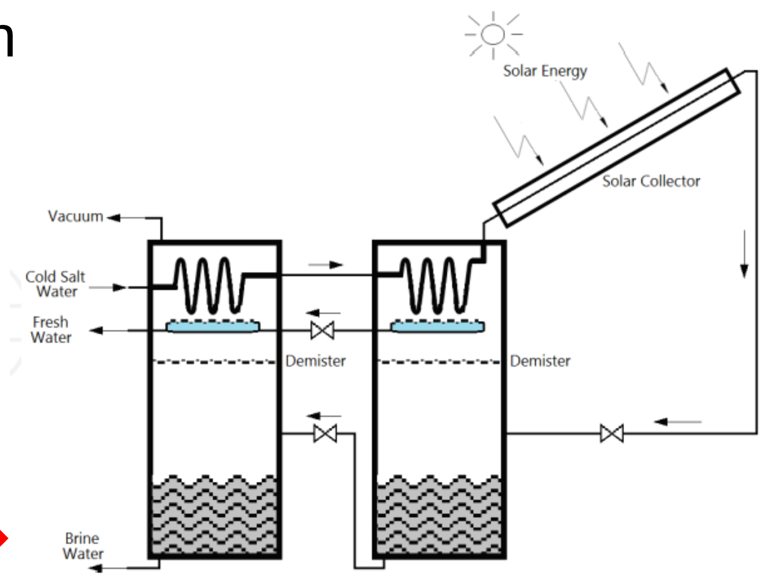
Sharshir et al., Appl. Thermal. Eng., 2017

Solar water desalination

- Thermal teachnologies:
  - Multi-stage distillation:
    - Thermal need 190-282 MJ/m^3
    - Electrical need 2.5-5 kW/m^3
    - Temperature 90 to 110 °C
    - 10'000-35'000 m^3/day
    - 4-40 stages
    - Water quality ~10 ppm

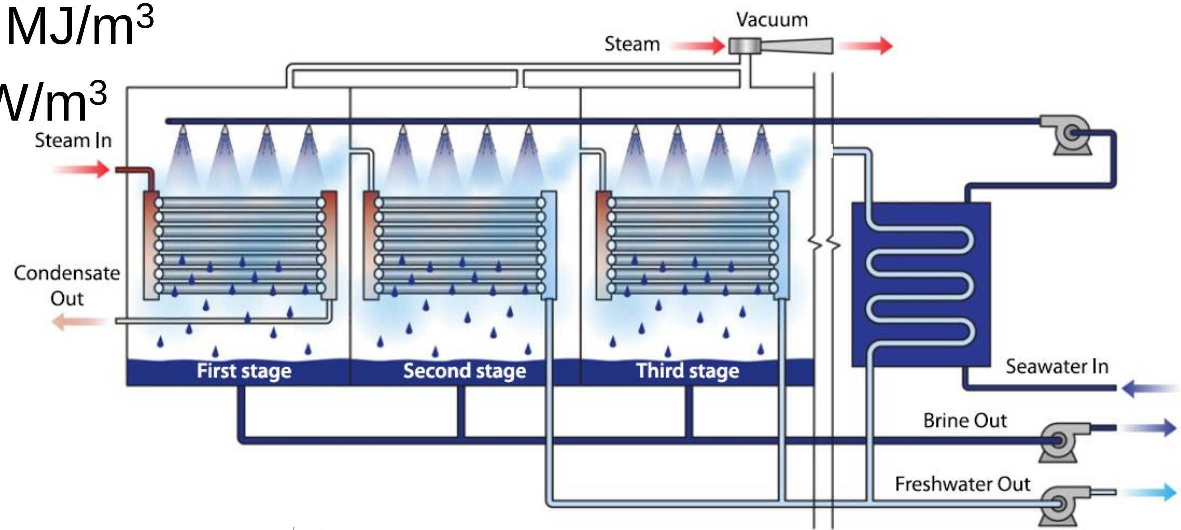


  - Solar-driven

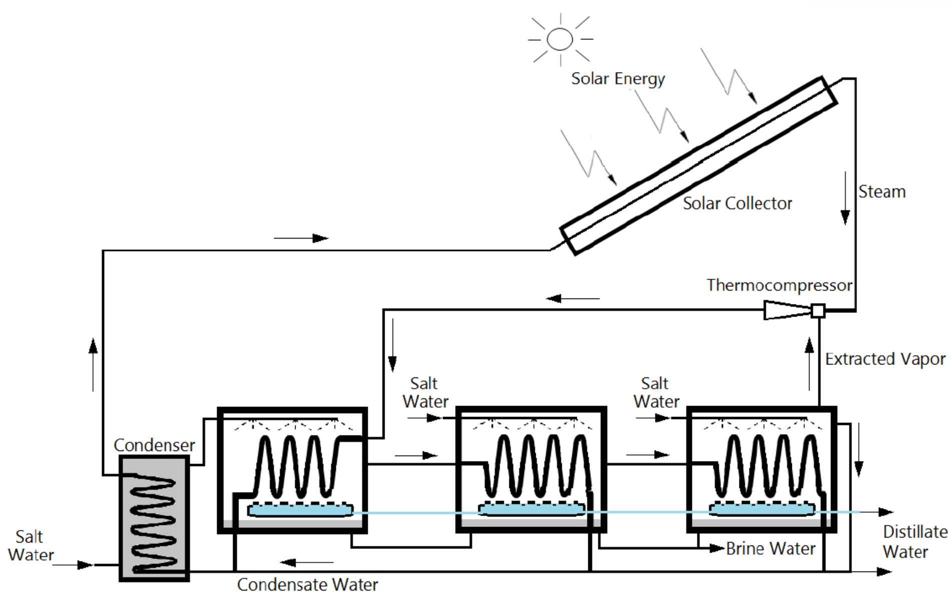


Solar water desalination

- Thermal teachnologies:
  - Multi effect distillation:
    - Thermal need 145-230 MJ/m^3
    - Electrical need 2.5-5 kW/m^3
    - Temperature <100°C
    - 600-30'000 m^3/day
    - 2-16 effects
    - Water quality ~10 ppm

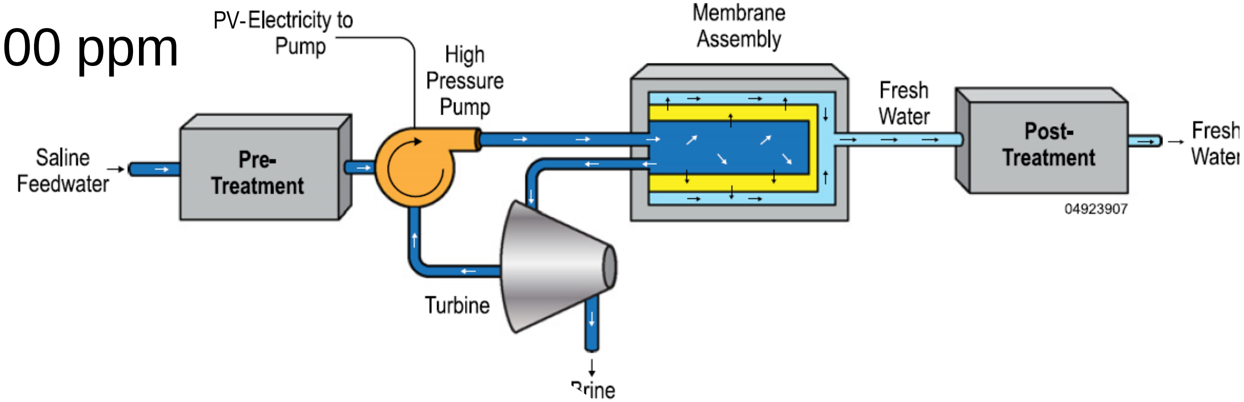


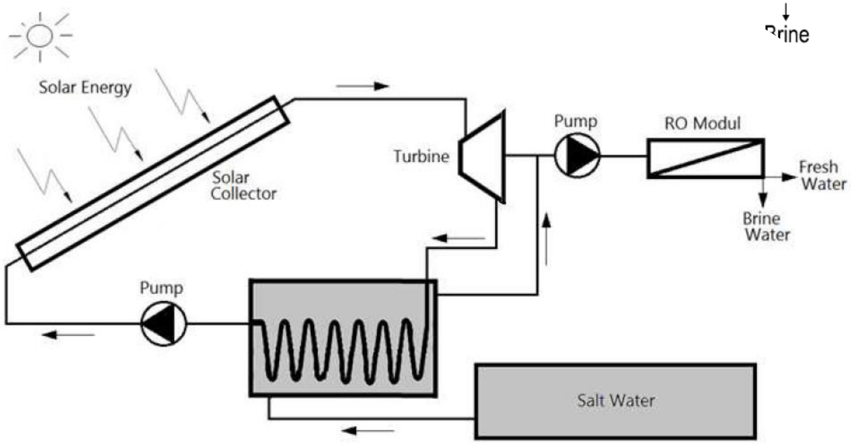
  - Solar-driven



Solar water desalination

- Membrane-based technologies:
  - Reverse osmosis:
    - No thermal energy
    - Electrical need 2.1-6 kW/m^3
    - 10-27 bar for brakish water, 55-85 bar for seawater
    - Up to 395'000 m^3/day
    - Water quality 400-500 ppm
  - Solar-driven



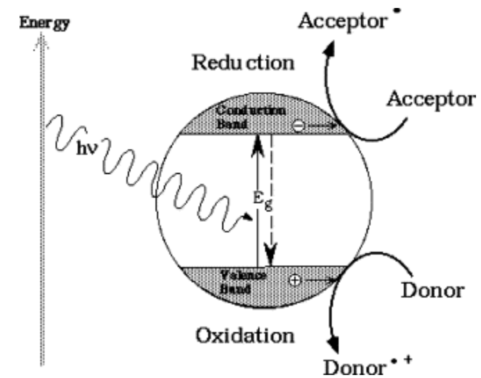


Solar water purification

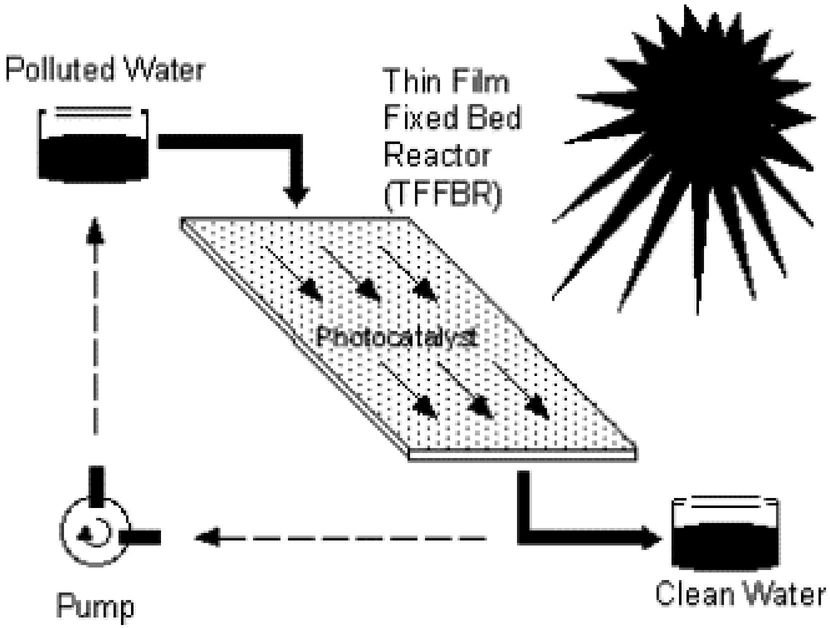
- Photocatalytic water purification:

Degradation of organic pollutants in water and air streams by advanced oxidation processes

Titanium-oxid widely used (band gap: 3.2 eV)

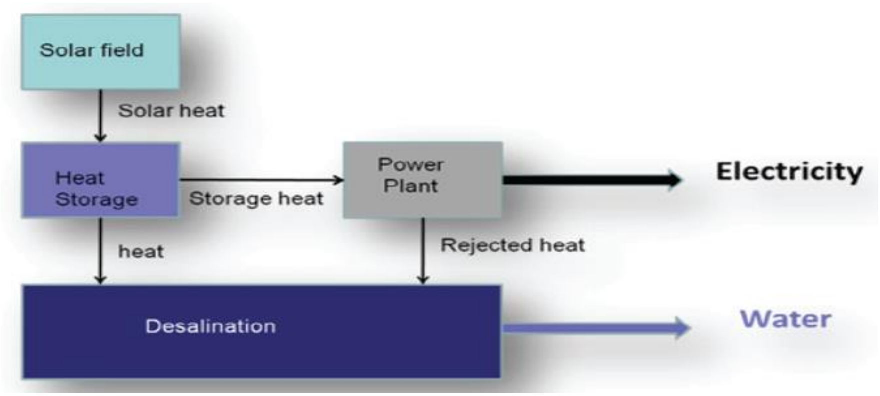


Bahnemann, Solar Energy, j.solener.2004.03.031, 2004



Solar co-generation

- Concentrated solar for desalination, and power
- Case study Cyprus



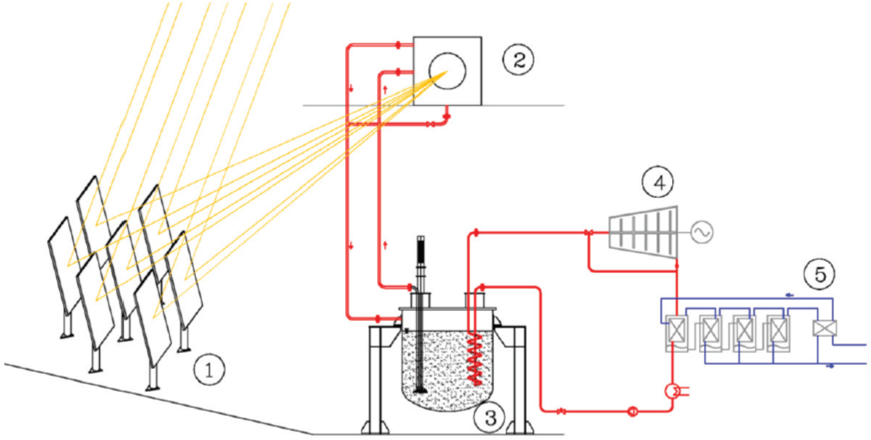
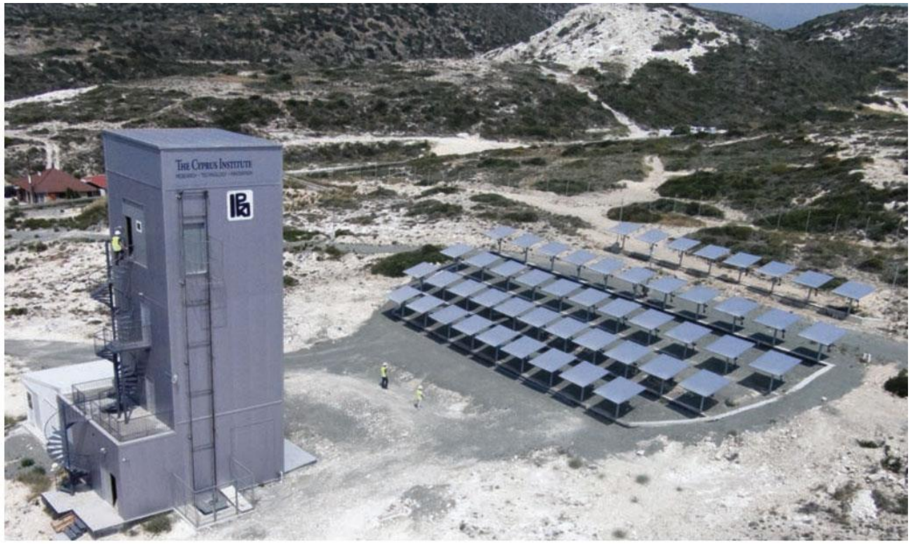


FIGURE 2. Simplified schematic of the plant layout, with the following components schematically indicated: 1) the heliostat field, 2) the central receiver, 3) the molten salt storage tank, 4) the steam engine and 5) the MED desalination unit



Pentakomo Field Facility: The rotating heliostats collect the light of the sun as it moves across the sky and redirect it onto a receiver on the top of the tower

Papanicolas et al., AIP Conf. Proc., 10.1063/1.4949196, 2016

Solar electricity and heat and water treatment

Solar co-generation

- Concentrated solar for heat, cooling, desalination, and power
- Case study Chile: