Solar Photovoltaics & Energy Systems

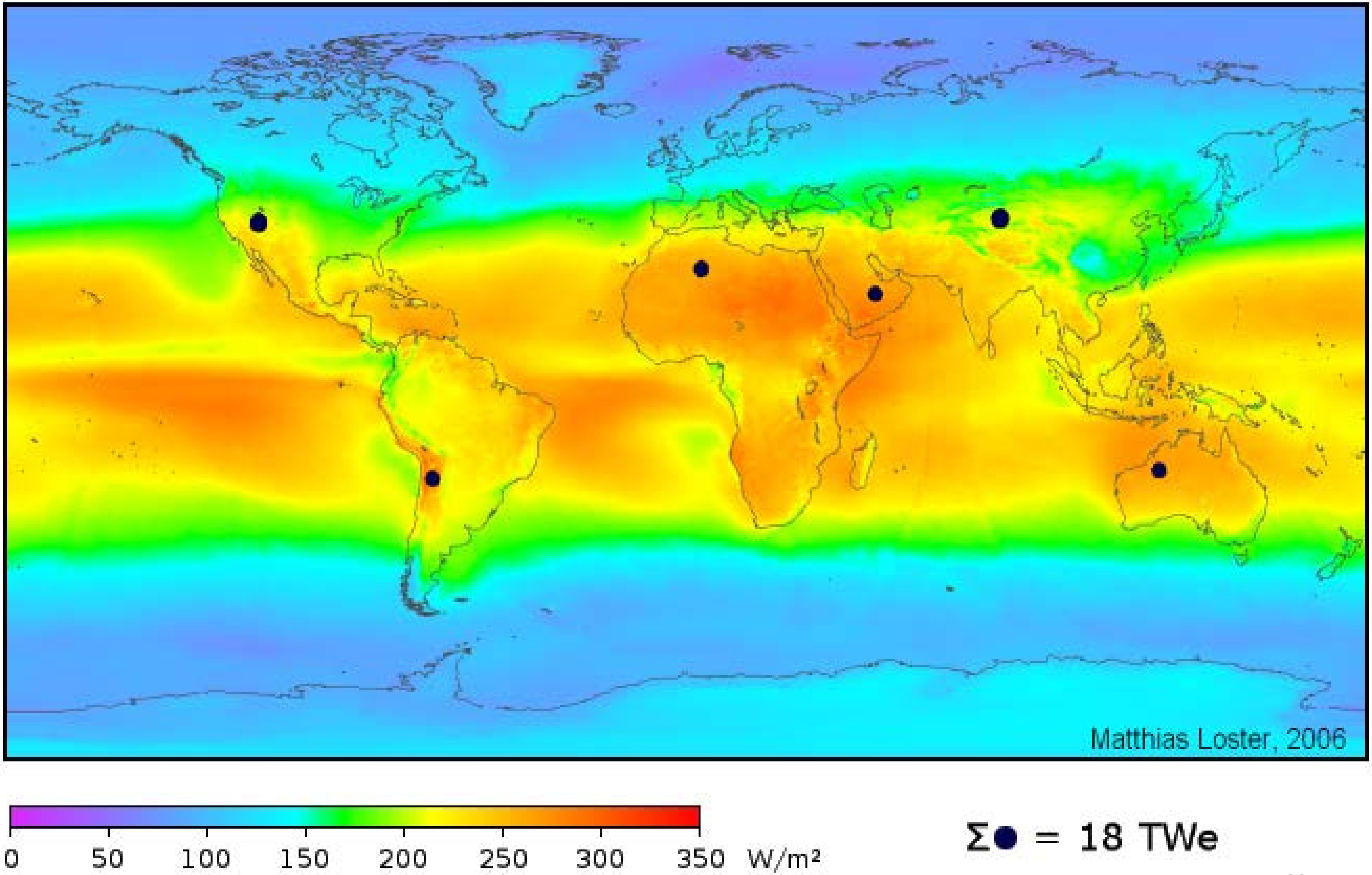
Lecture 2. Thermodynamics of solar energy conversion and solar thermal energy conversion

ChE-600

Kevin Sivula, Spring 2016

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

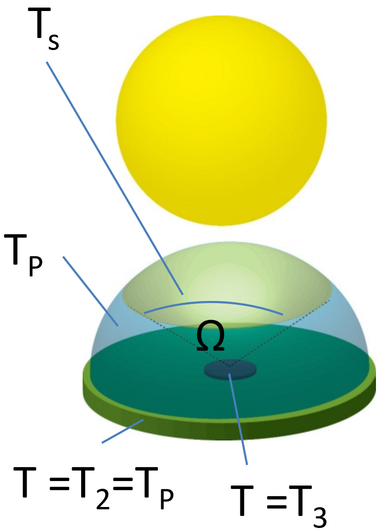
Averaged Solar Radiation 1990-2004



$\Sigma \bullet$ = 18 TWe

Assuming 8% energy conversion efficiency

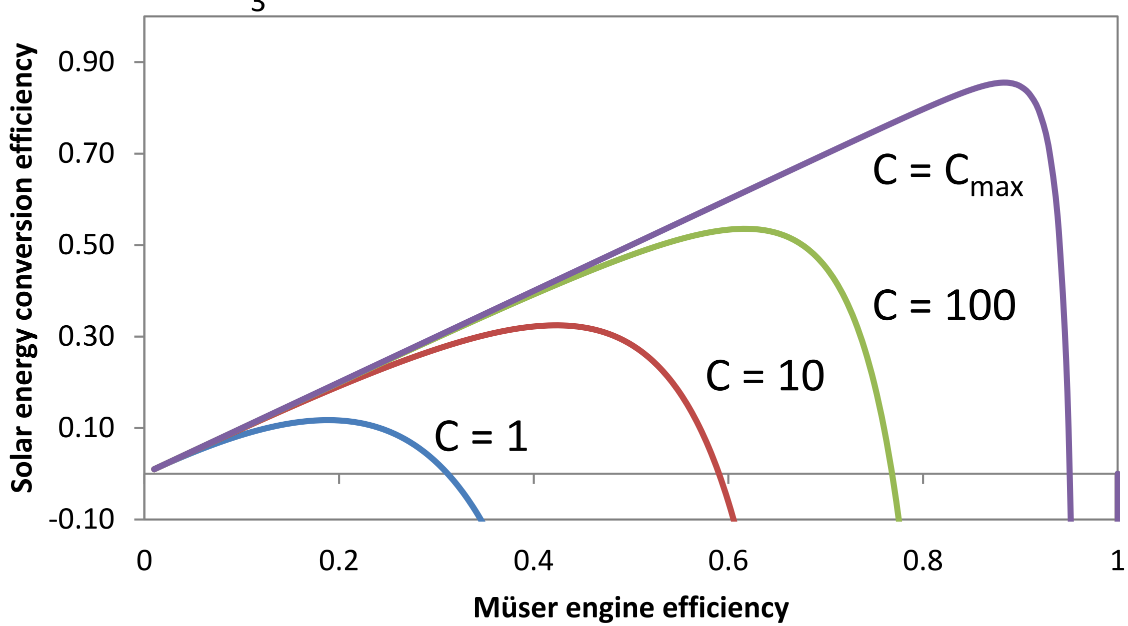
The Müser Engine with a concentrator

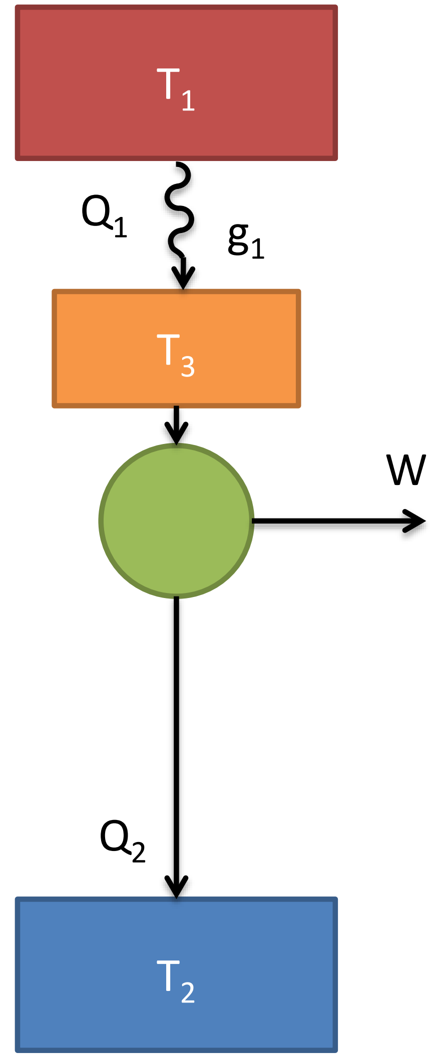


$$Q_1 = \sigma\left[Cf T_s^4 + (1 - Cf) T_p^4 - T_3^4\right]$$

Solar energy efficiency:

$$W = \eta_{solar} C f \sigma T_s^4$$





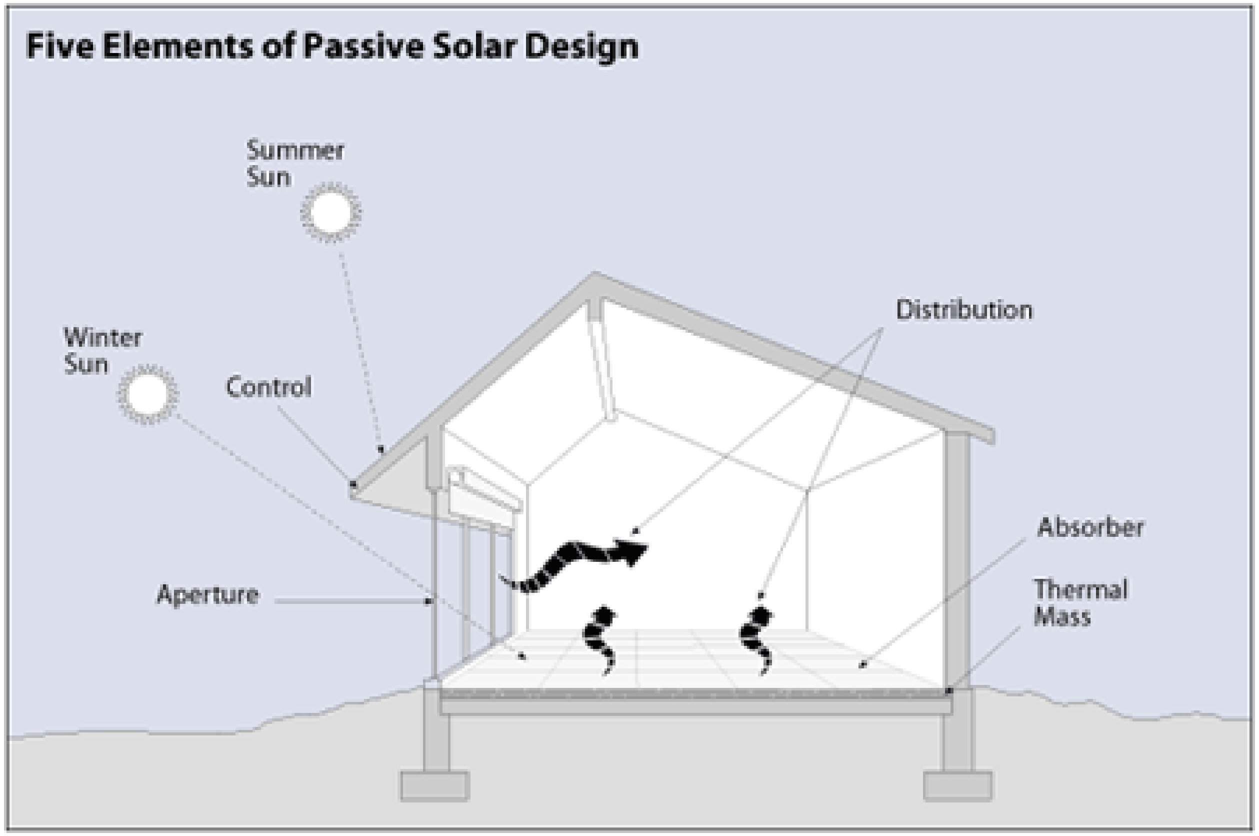
Introduction to solar thermal energy

- Low-medium temperature collectors

- High temperature collectors

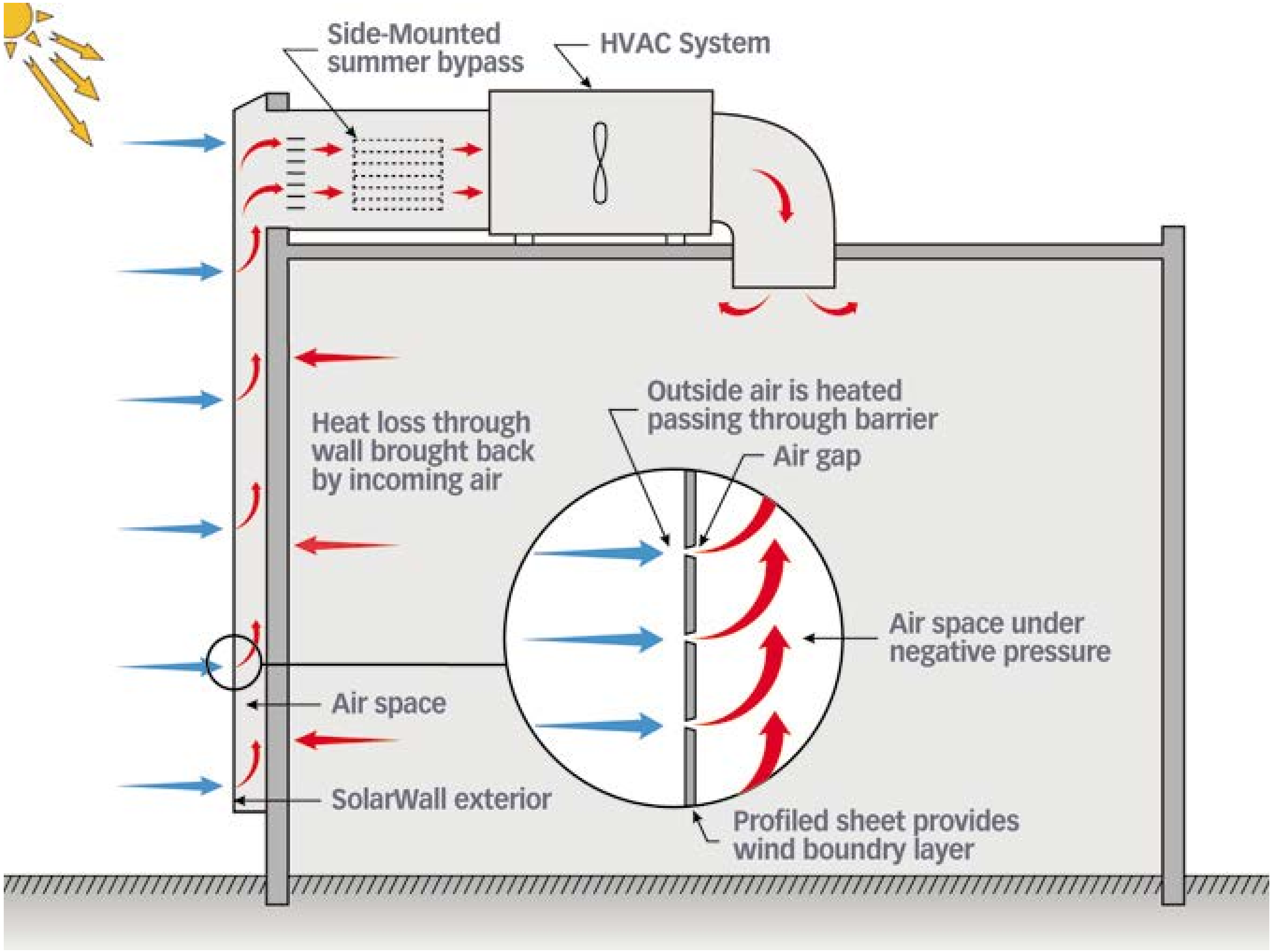
Low temperature collectors - examples

- Thermal mass methods



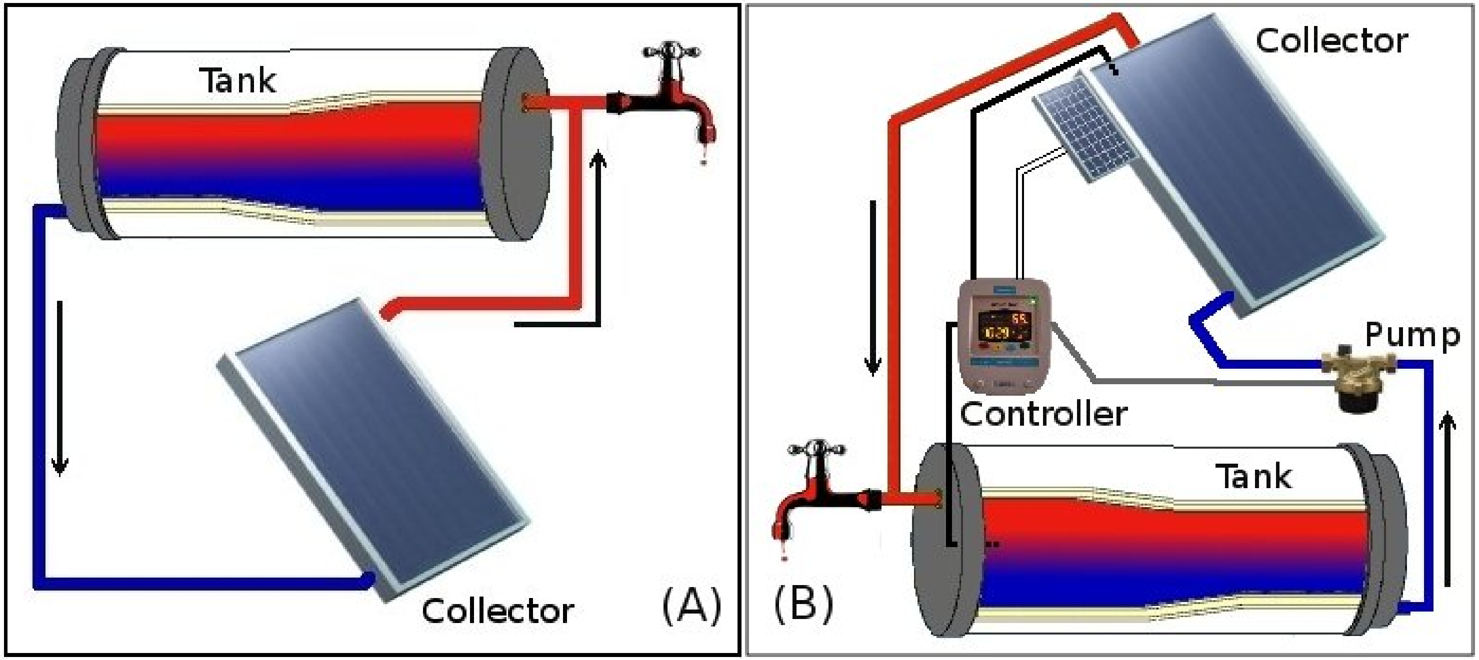
Low temperature collectors - examples

- Solar air heat



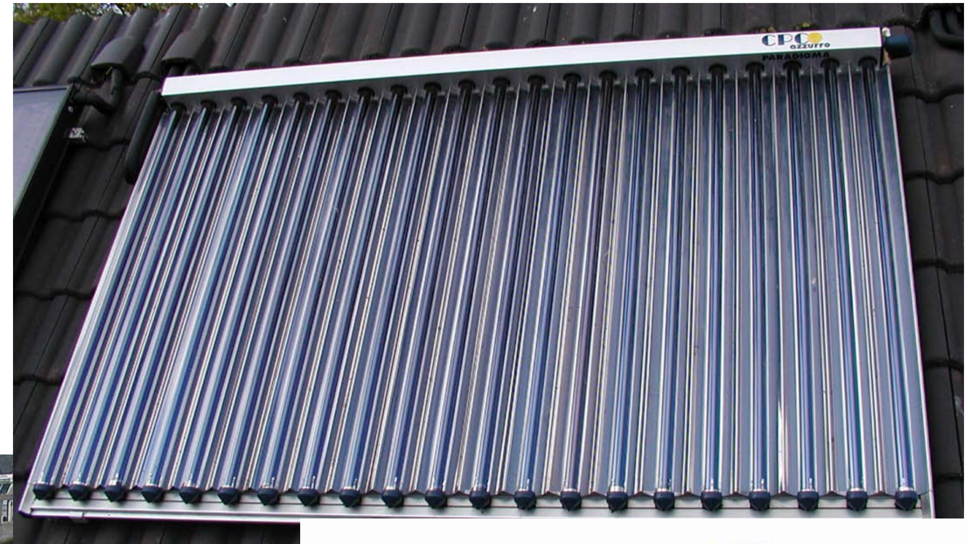
Low temperature collectors - examples

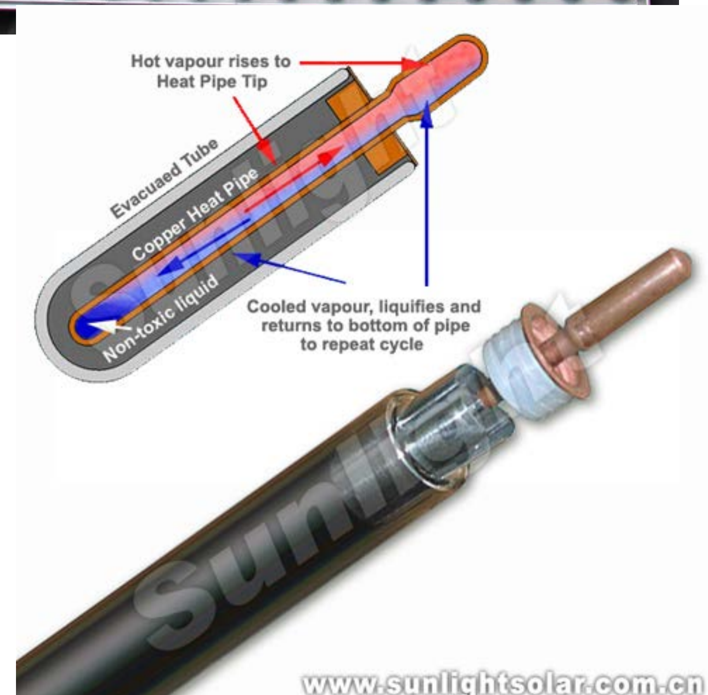
- Solar water heating



Low temperature collectors - examples

- Solar water heating
  - Flat plate collectors
  - Evacuated tube collectors





Solar water heating

Daily energy production ($kW_{th}.h$) of five solar thermal systems. The evac tube systems used below both have 20 tubes					
Technology	Flat plate	Flat plate	Flat plate	Evac tube	Evac tube
Configuration	Direct active	Thermosiphon	Indirect active	Indirect active	Direct active
Overall size (m^2)	2.49	1.98	1.87	2.85	2.97
Absorber size (m^2)	2.21	1.98	1.72	2.85	2.96
Maximum efficiency (1 sun)	0.68	0.74	0.61	0.57	0.46
Energy production (kW.h/day): – Insolation 3.2 kW.h/m²/day (temperate, e.g. Zurich, Switzerland)*	5.3	3.9	3.3	4.8	4.0
– Insolation 6.5 kW.h/m²/day (tropical, e.g. Phoenix, USA)	11.2	8.8	7.1	9.9	8.4

Solar water heating

Top countries using solar thermal power, worldwide (GW_{th})[10][69][70][71][72][73][74]

#	Country	2005	2006	2007	2008	2009	2010	2011	2012	2013
1	China	55.5	67.9	84.0	105.0	101.5	117.6	-	-	262.3[75]
–	*EU*	11.2	13.5	15.5	20.0	22.8	23.5	25.6	29.7	31.4
2	United States	1.6	1.8	1.7	2.0	14.4	15.3	-	-	16.8[75]
3	Germany	–	–	–	7.8	8.9	9.8	10.5	11.4	12.1
4	Turkey	5.7	6.6	7.1	7.5	8.4	9.3	-	-	11.0[75]
5	Australia	1.2	1.3	1.2	1.3	5.0	5.8	-	-	5.8[75]
6	Brazil	1.6	2.2	2.5	2.4	3.7	4.3	-	-	6.7[75]
7	Japan	5.0	4.7	4.9	4.1	4.3	4.0	-	-	3.2[75]
8	Austria	–	–	–	2.5	3.0	3.2	2.8	3.4	3.5
9	Greece	–	–	–	2.7	2.9	2.9	2.9	2.9	2.9
10	Israel	3.3	3.8	3.5	2.6	2.8	2.9	-	-	2.9[75]
	World (GW_{th})	**88**	**105**	**126**	**149**	**172**	**196**	-	-	-

High temperature collectors

- Mainly used for electricity production in process generally referred to as concentrated solar power (CSP).
- Modern systems continue to use heat to make steam to drive a turbine.

Tower type

Parabolic trough

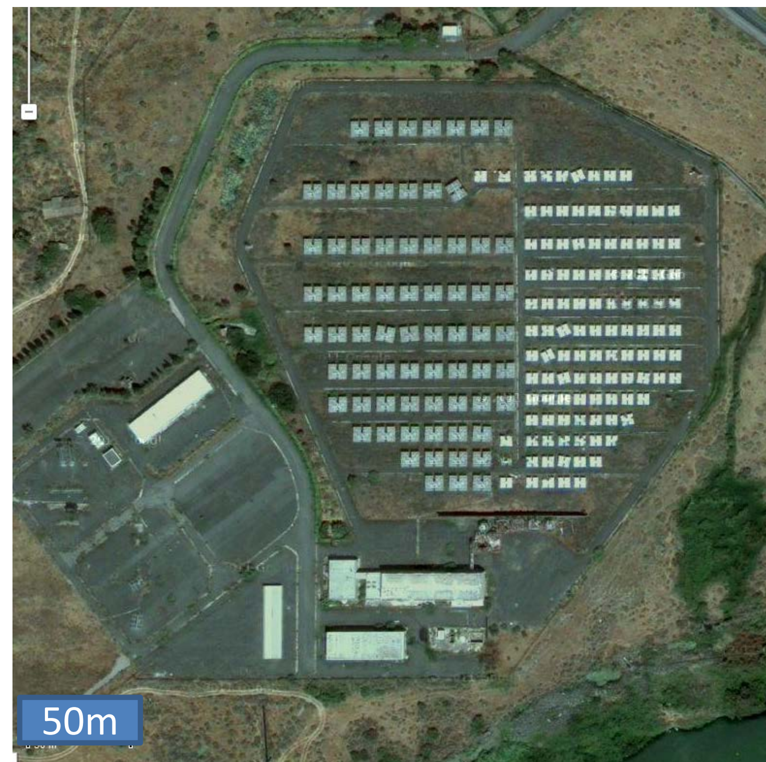
Fresnel reflectors

Dish Stirling

An example of concentrated solar power

- 182 flat mirrors
- Two axis control
- 55 m tower height
- Cavity type receiver

- "Eurelios" at Adrano (Sicily Italy)
- Type: Mirror field/central receiver
- Designed for electricity production (nominal rating 1 MW)
- Completed in 1980



“Eurelios” at Adrano in detail

eutectic mixture of potassium nitrate (53%), sodium nitrite (40%) and sodium nitrate (7%)

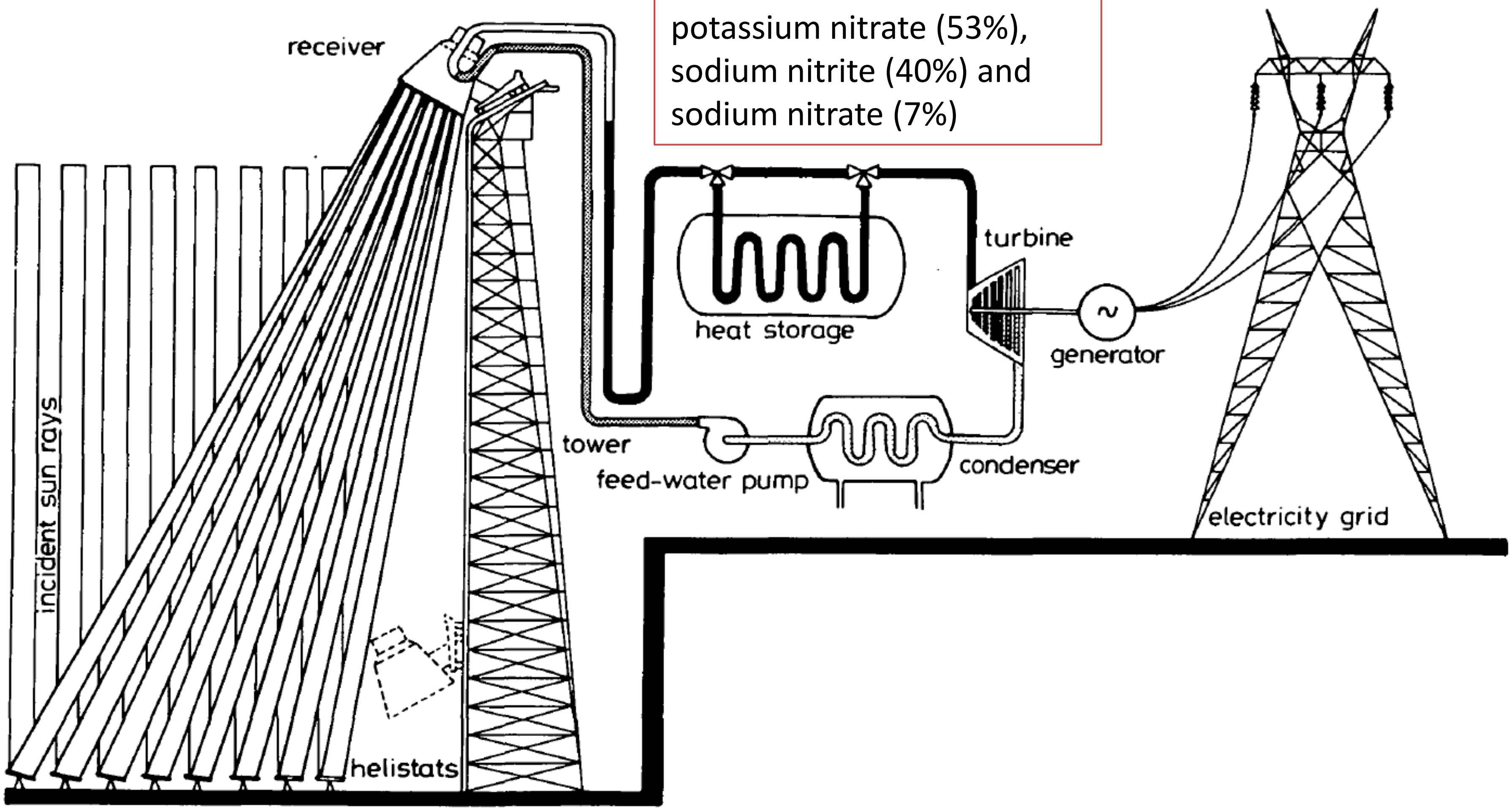
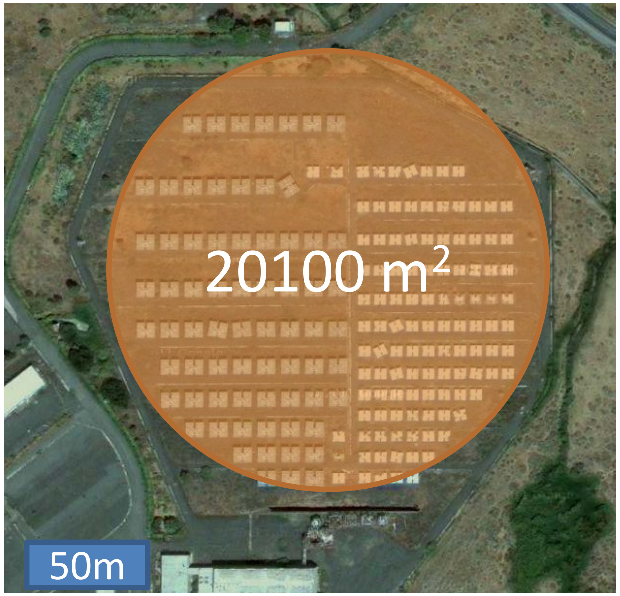


Fig. 2 *Schematic plant system*

Joachim Gretz, IEE Proceedings, 1987, *134*, 399

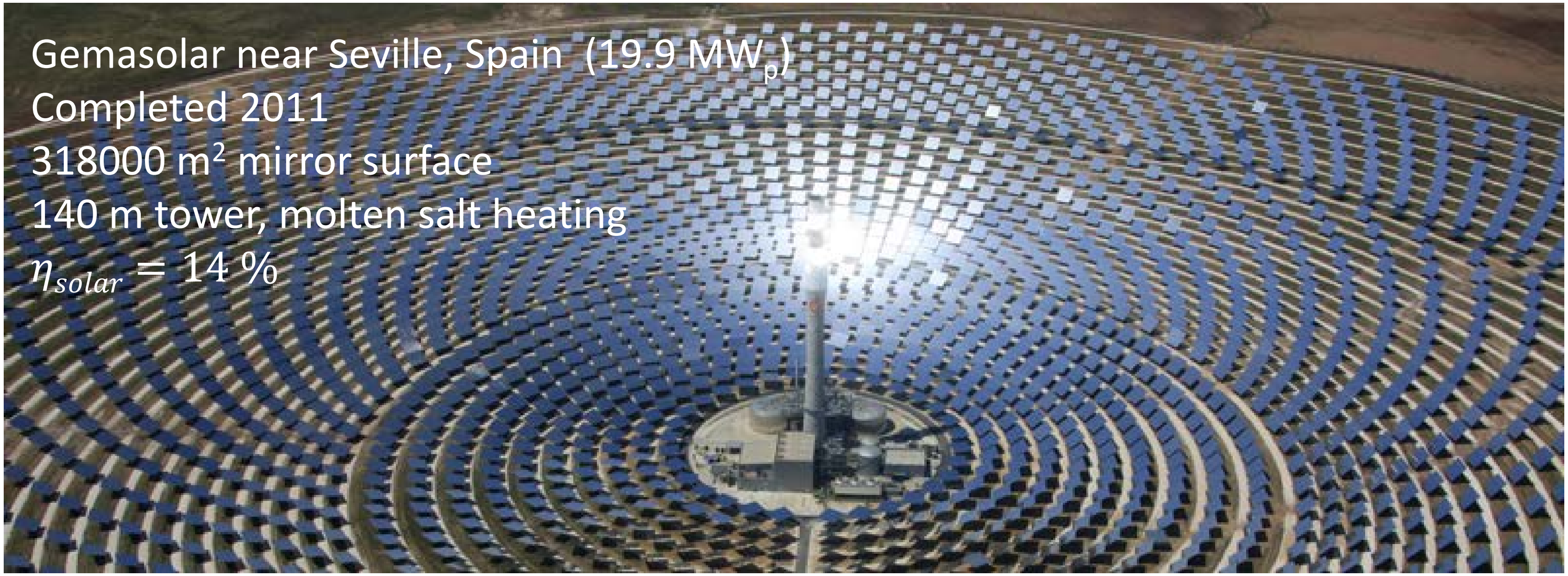
Analysis of "Eurelios" at Adrano



- 6216 m² mirror surface
- Aperture of 16 m² on receiver
- $C = \frac{6216\ \mathrm{m}^2}{16\ \mathrm{m}^2} = 389$
- $\max(\eta_{solar}) = 63.7\%$
- $\eta_{solar} = \frac{power\ output}{power\ input} = \frac{750000\ \mathrm{W}}{920\ \mathrm{W\,m^{-2}}\ 6216\ \mathrm{m}^2}$
- $\eta_{solar} = 13.1\ \%\ (14.5\ \%\ \text{claimed})$
- Based on land area $\eta_{solar} = 4.1\ \%$

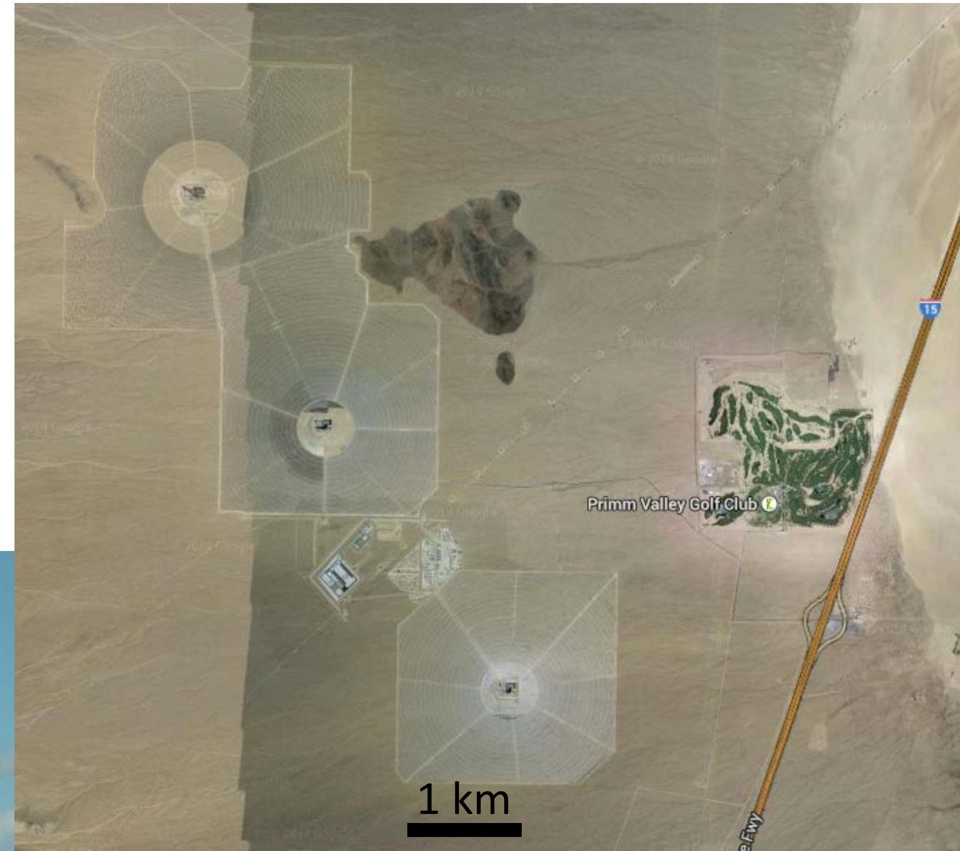
Solar power tower

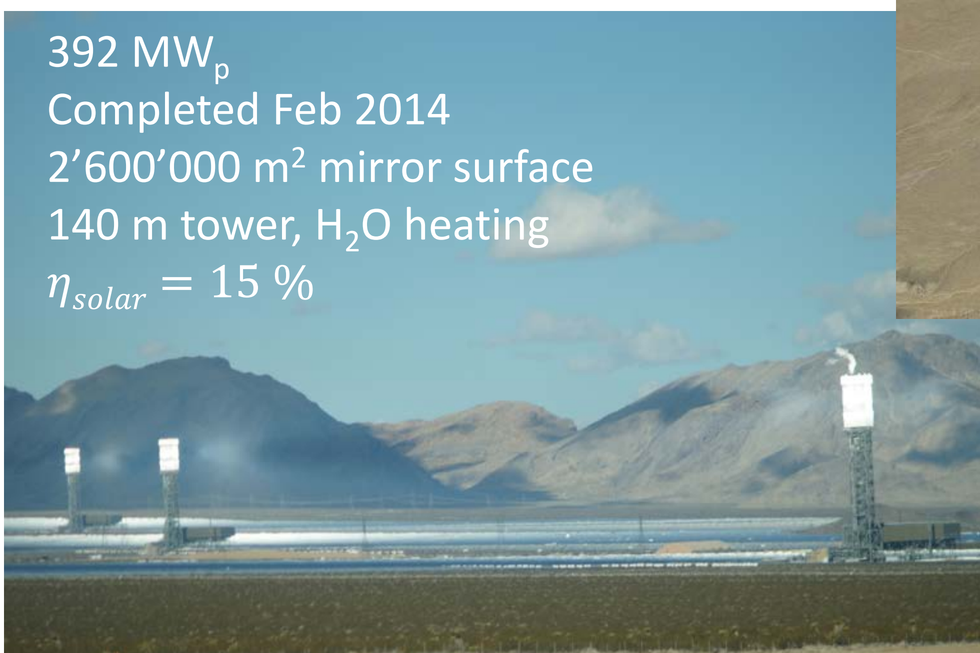
PS10 near Seville, Spain (11MW$_p$)
Completed 2006
74880 m^2 mirror surface
115 m tower, H_2O heating
$\eta_{solar} = 15.5\ \%$



Gemasolar near Seville, Spain (19.9 MW$_p$)
Completed 2011
318000 m^2 mirror surface
140 m tower, molten salt heating
$\eta_{solar} = 14\ \%$

Ivanpah Solar Power Facility





392 MW_p
Completed Feb 2014
2’600’000 m^2 mirror surface
140 m tower, H_2O heating
$\eta_{solar} = 15\ \%$

Economic viability of Solar power towers

Nathaniel Bullard, a solar analyst at Bloomberg New Energy Finance, has calculated that the cost of electricity at the Ivanpah Solar Power Facility, a project under construction in Southern California, will be lower than that from photovoltaic power and about the same as that from natural gas.

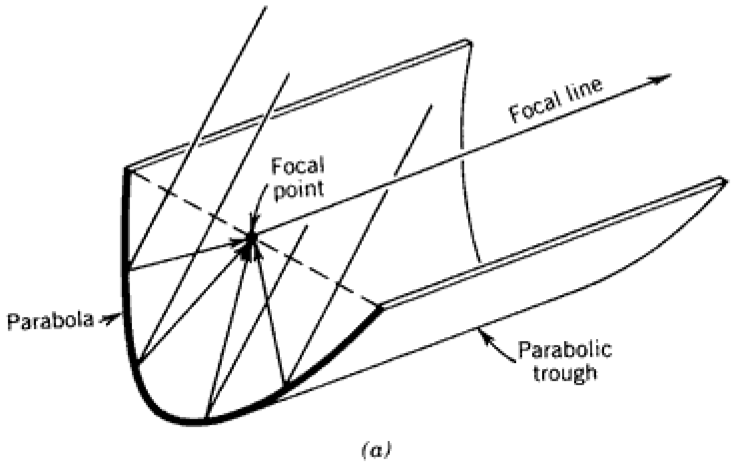
Google invested US$168 million on BrightSource

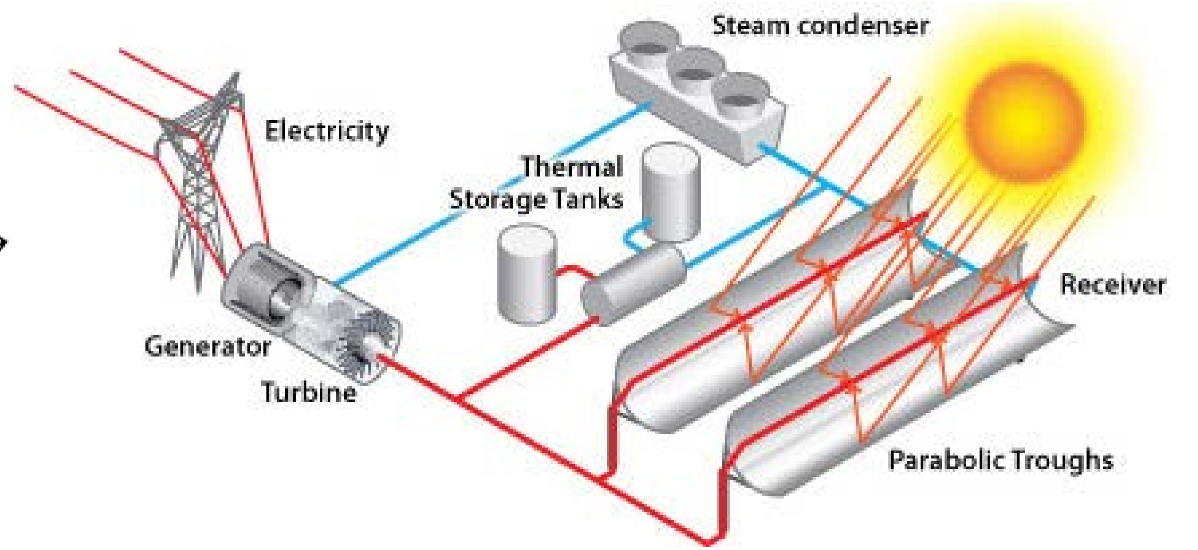
However, in November 2011, Google announced that they would not invest further in CSP projects due to the rapid price decline of photovoltaics. Google invested US$168 million on BrightSource…. There are insufficient installations to clearly establish the learning curve

As of March 2012, there were 1.9 GW of CSP installed, with 1.8 GW of that being parabolic trough

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

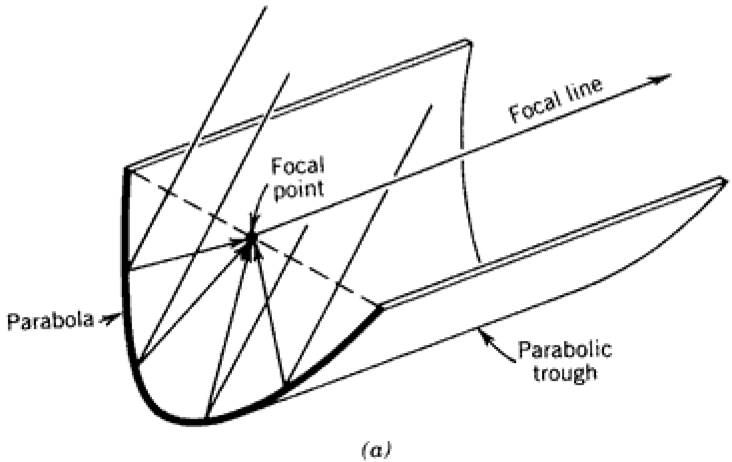
Parabolic trough

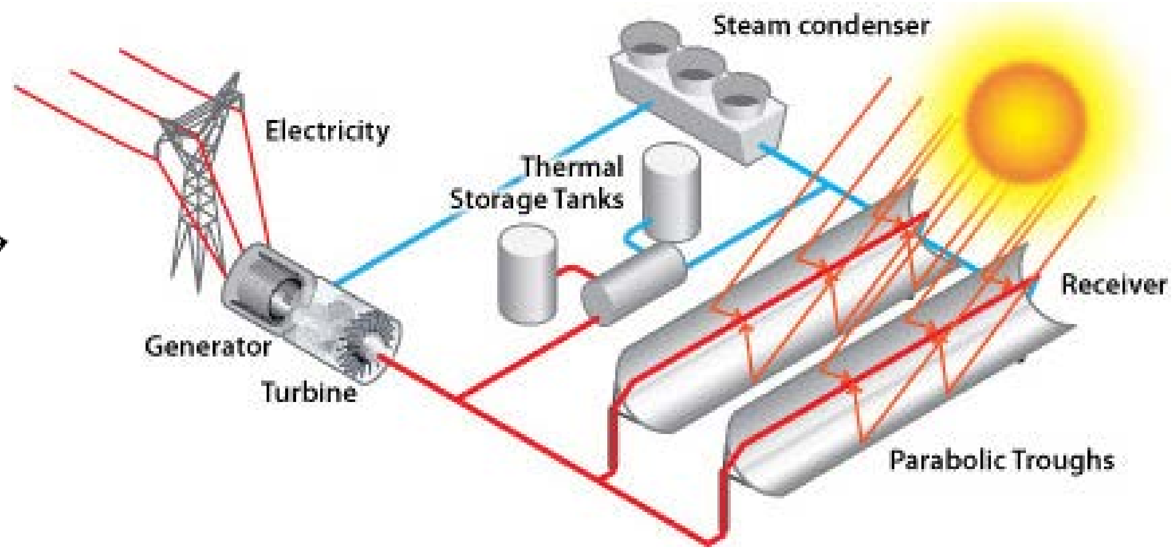




- Concentration factor = 30
- Collection of radiation can be up to 73% (typically about 60%)
- $\eta_{solar} = 15\%$
- Heat transfer fluid is oil (up to 400°C)

Parabolic trough

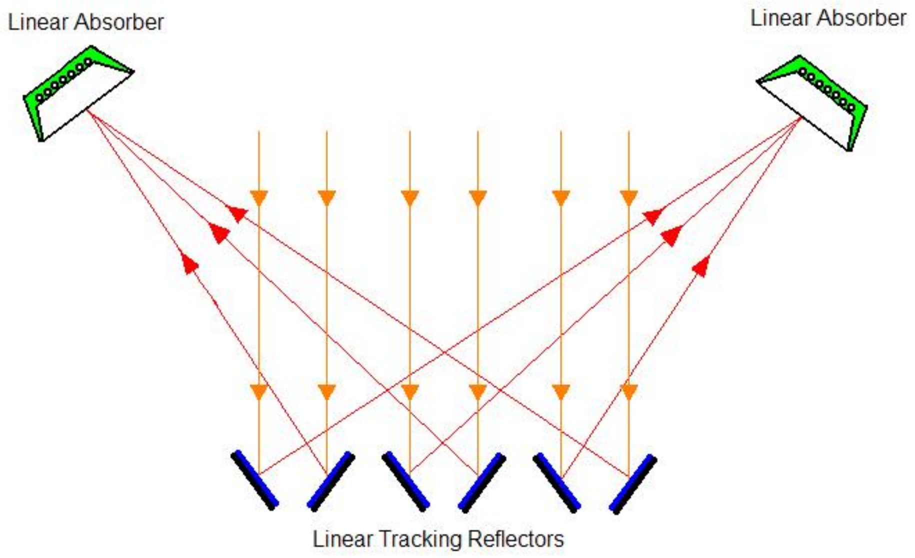




Power plants	Installed capacity (MW)	Yearly production (GWh)	Country	Developer/ Owner	Completed
Solar Energy Generating Systems	354	2037	United States	NextEra Energy Resources	1990
Nevada solar one	64	134	United States	SolarReserve	2007
Andasol Solar Power Station	150	180	Spain	ACS Group	2009

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

Compact linear Fresnel reflector

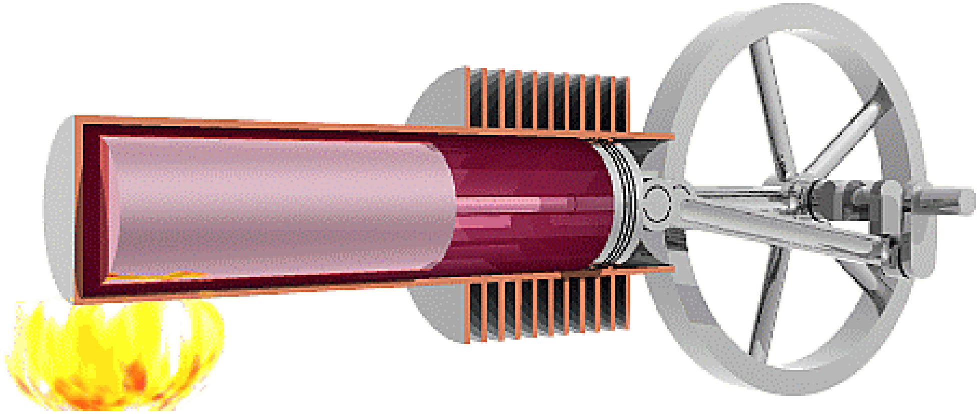


- Concentration factor = 40
- Reduced cost over parabolic trough

Power plants	Installed capacity (MW)	Yearly production (GWh)	Country	Developer/ Owner	Completed
PE1	1.4	--	Germany	Novatec Biosol	2009
PE2	*30*	--	Spain	Novatec Biosol	*2014*
Kimberlina Solar Thermal	5	--	USA	AREVA Solar	2008

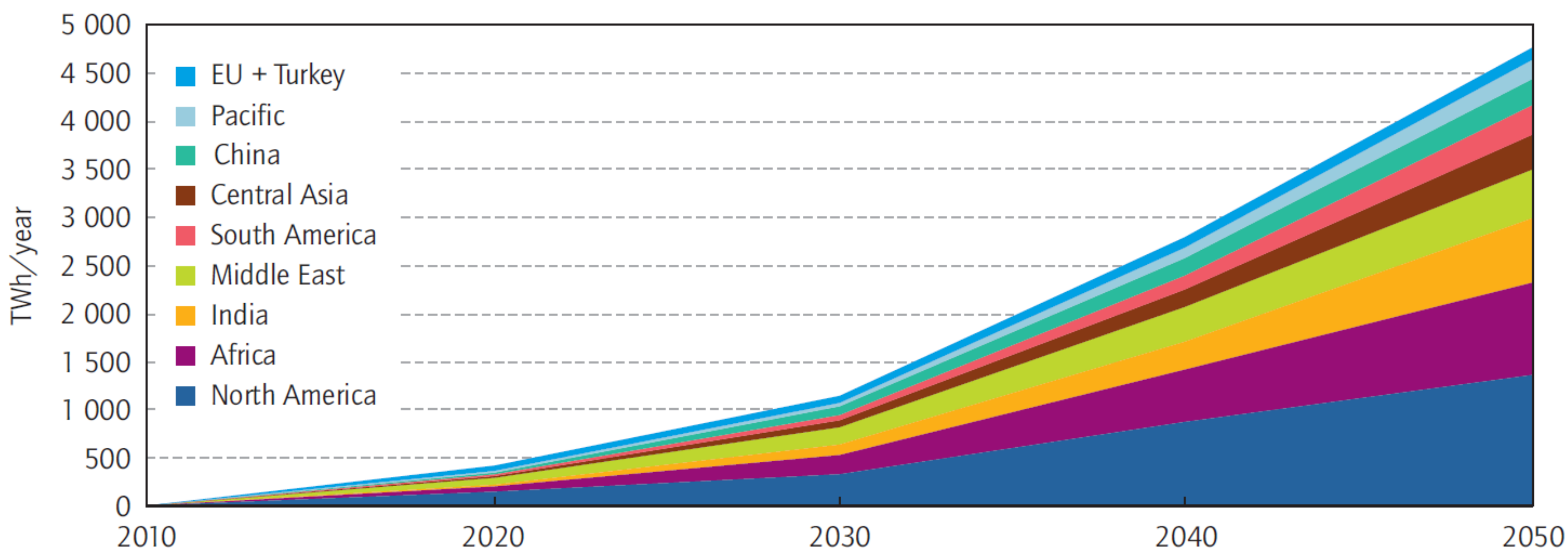
Dish sterling

- high efficiency η_{solar} =29.4%
- autonomous operation
- modularity



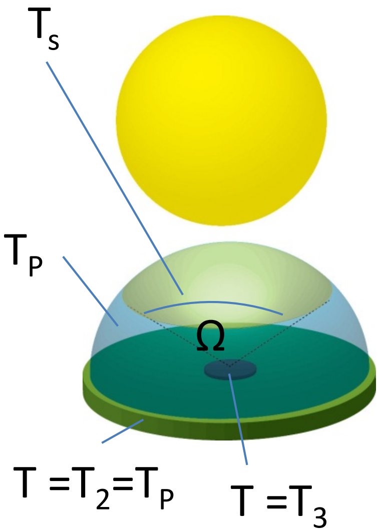
Concentrated solar power summary

- Total solar thermal energy:
  - ≈200 GW_{th} installed
- Concentrated solar power for electricity production:
  - 4.9 GW installed
  - 1.23 GW under construction
  - 3.4 GW planned (announced projects)



http://www.iea.org/papers/2010/csp_roadmap.pdf

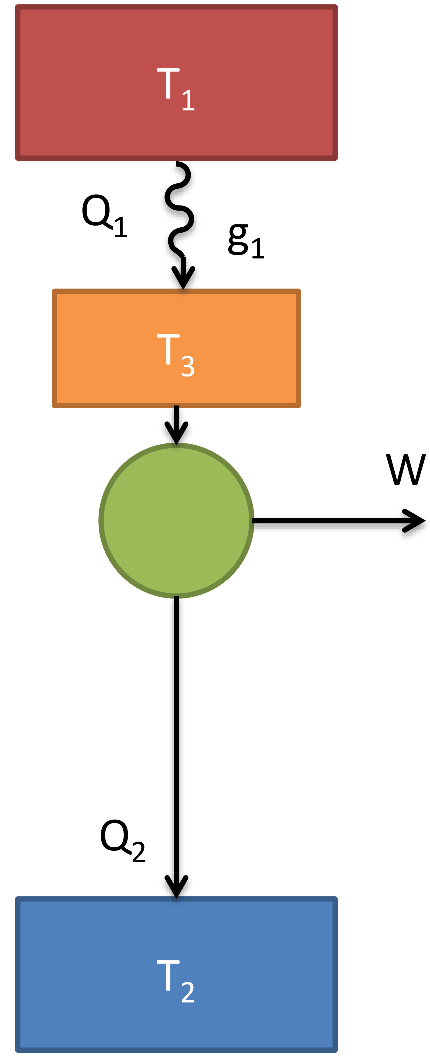
The Müser Engine with a concentrator

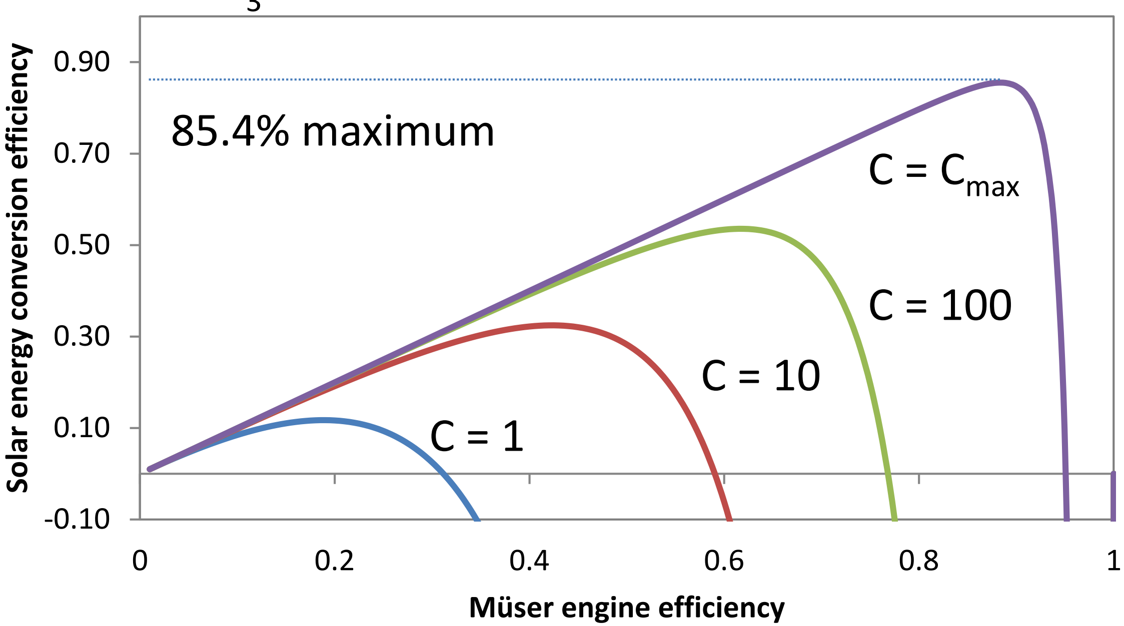


$$Q_1 = \sigma\left[CfT_s^4 + (1 - Cf)T_p^4 - T_3^4\right]$$

Solar energy efficiency:

$$W = \eta_{solar} Cf\sigma T_s^4$$

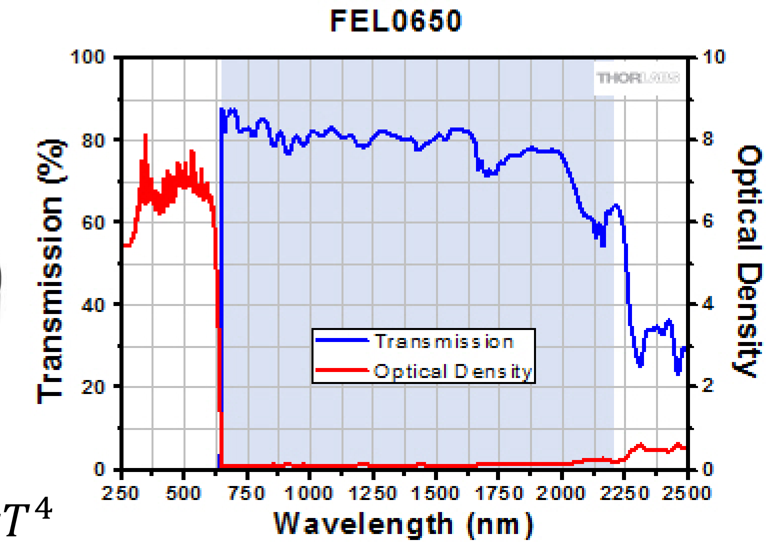




The Müser Engine with a band gap

A "selective black body" can be defined

$$\varepsilon(\lambda) = \begin{cases} 0 \; for \; E < E_g \\ 1 \; for \; E > E_g \end{cases}$$

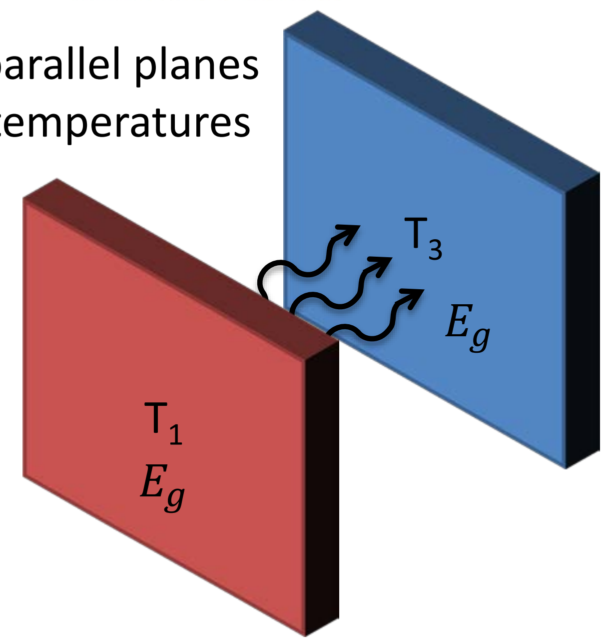


Recall that:

$$Q/A = \pi \int_{\lambda=0}^{\infty} B_{\lambda}(T)d\lambda = \int_{\lambda=0}^{\infty} \frac{2\pi hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k_B T}}-1} d\lambda = \sigma T^4$$

$$E = \frac{hc}{\lambda}$$ (change variables from λ to E)

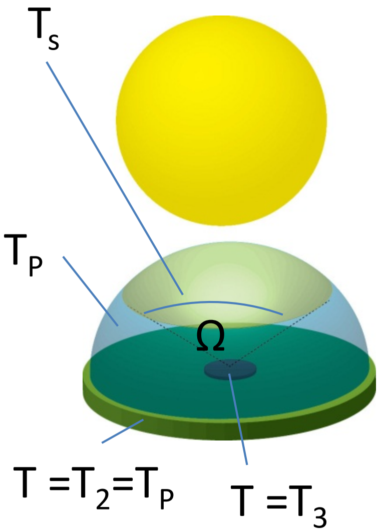
Consider two parallel planes with different temperatures but same E_g



Then:

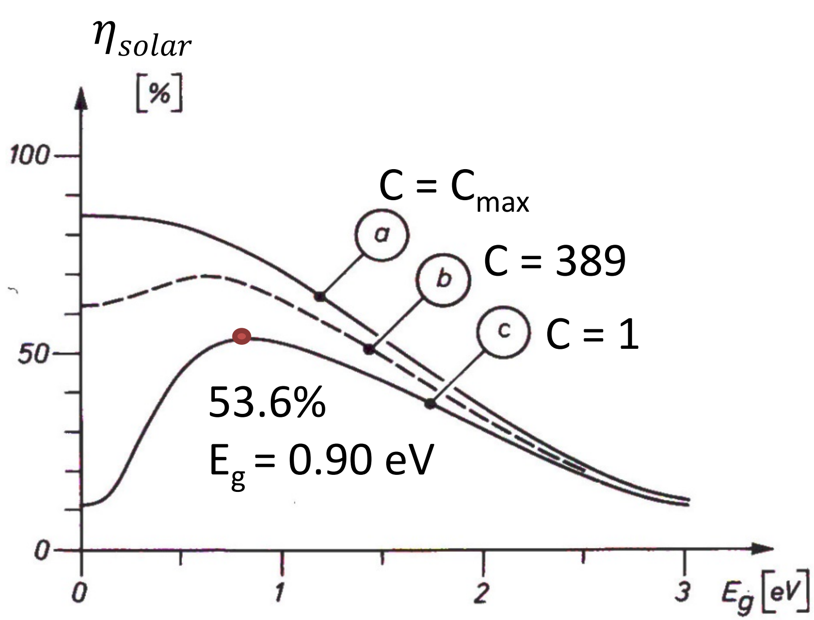
$$Q_1 = g\left[\int_{E_g}^{\infty} \frac{E^3 dE}{exp\left(\frac{E}{k_B T_1}\right)-1} - \int_{E_g}^{\infty} \frac{E^3 dE}{exp\left(\frac{E}{k_B T_3}\right)-1}\right]$$

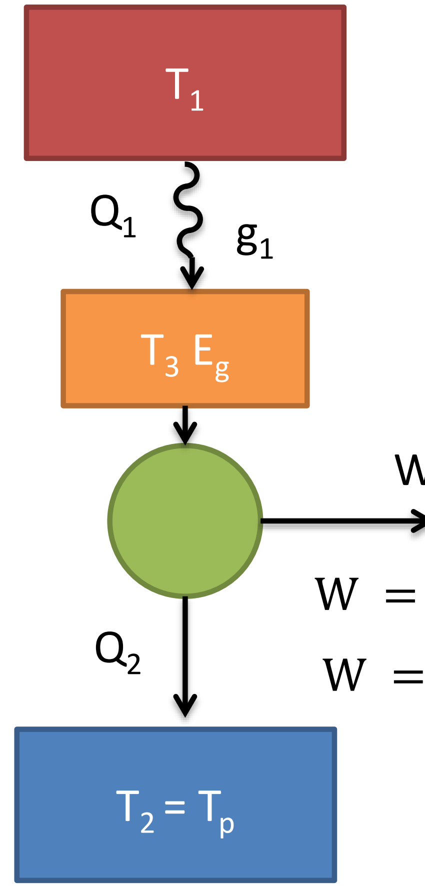
The Müser Engine with a band gap



Solar energy efficiency:

$$W = \eta_{solar} C f \sigma T_s^4$$





$$W = \eta_{solar} C f \sigma T_s^4$$

$$W = \eta_M Q_1$$

Then:

$$Q_1 = g_1 \left[Cf \int_{E_g}^{\infty} \frac{E^3 dE}{exp\left(\frac{E}{k_B T_s}\right) - 1} - (1 - Cf) \int_{E_g}^{\infty} \frac{E^3 dE}{exp\left(\frac{E}{k_B T_p}\right) - 1} - \int_{E_g}^{\infty} \frac{E^3 dE}{exp\left(\frac{E}{k_B T_p}(1 - \eta_M)\right) - 1} \right]$$

J. Phys. C: Solid State Phys., **15** (1982) 3967–3985. Printed in Great Britain

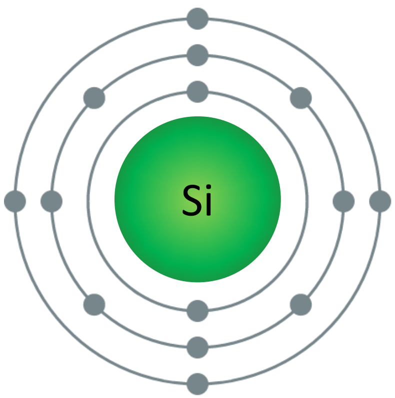
The chemical potential of radiation

P Würfel
Institut für Angewandte Physik, University of Karlsruhe, 7500 Karlsruhe, West Germany

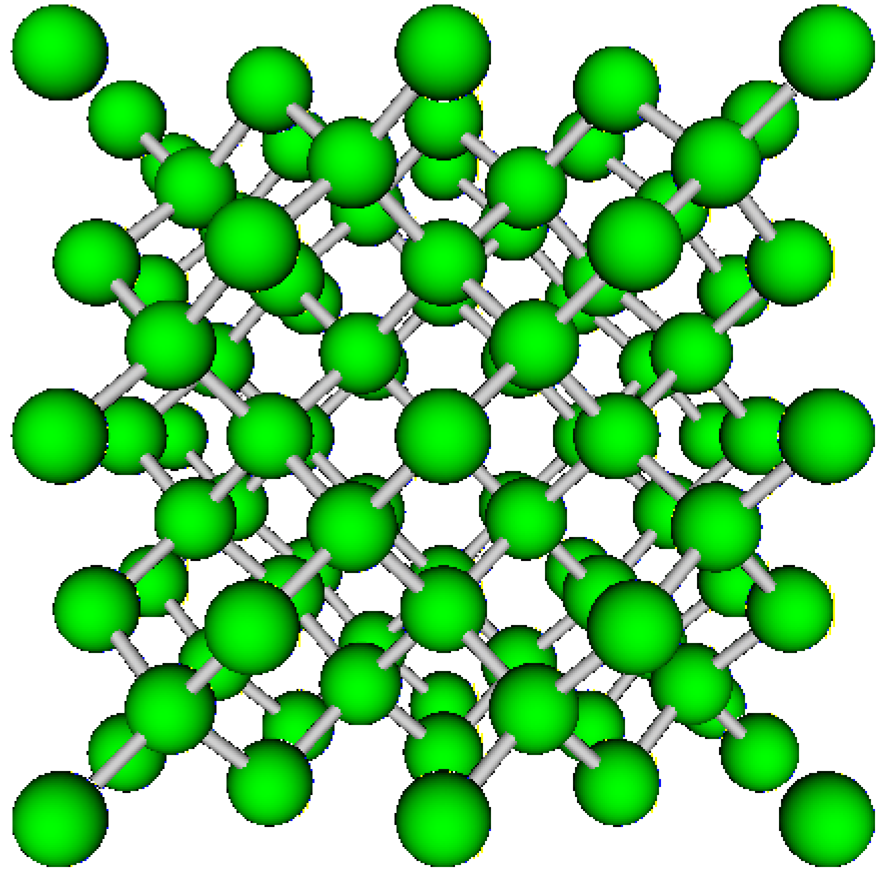
Received 3 September 1981, in final form 18 January 1982

Abstract. In a thermodynamic treatment electromagnetic radiation of any kind is described. The difference between thermal and non-thermal radiation is accounted for by introducing the chemical potential of photons. Instead of an effective temperature all kinds of radiation have the real temperature of the emitting material. As a result Planck's law for thermal radiation is extended to radiation of any kind. The concept of the chemical potential of radiation is discussed in detail in conjunction with light-emitting diodes, two-level systems, and lasers. It allows the calculation of absorption coefficients, of emission spectra of luminescent materials, and of radiative recombination lifetimes of electrons and holes in semiconductors. Theoretical emission spectra are compared with experimental data on GaAs light-emitting diodes and excellent agreement is obtained.

Description of a semiconductor

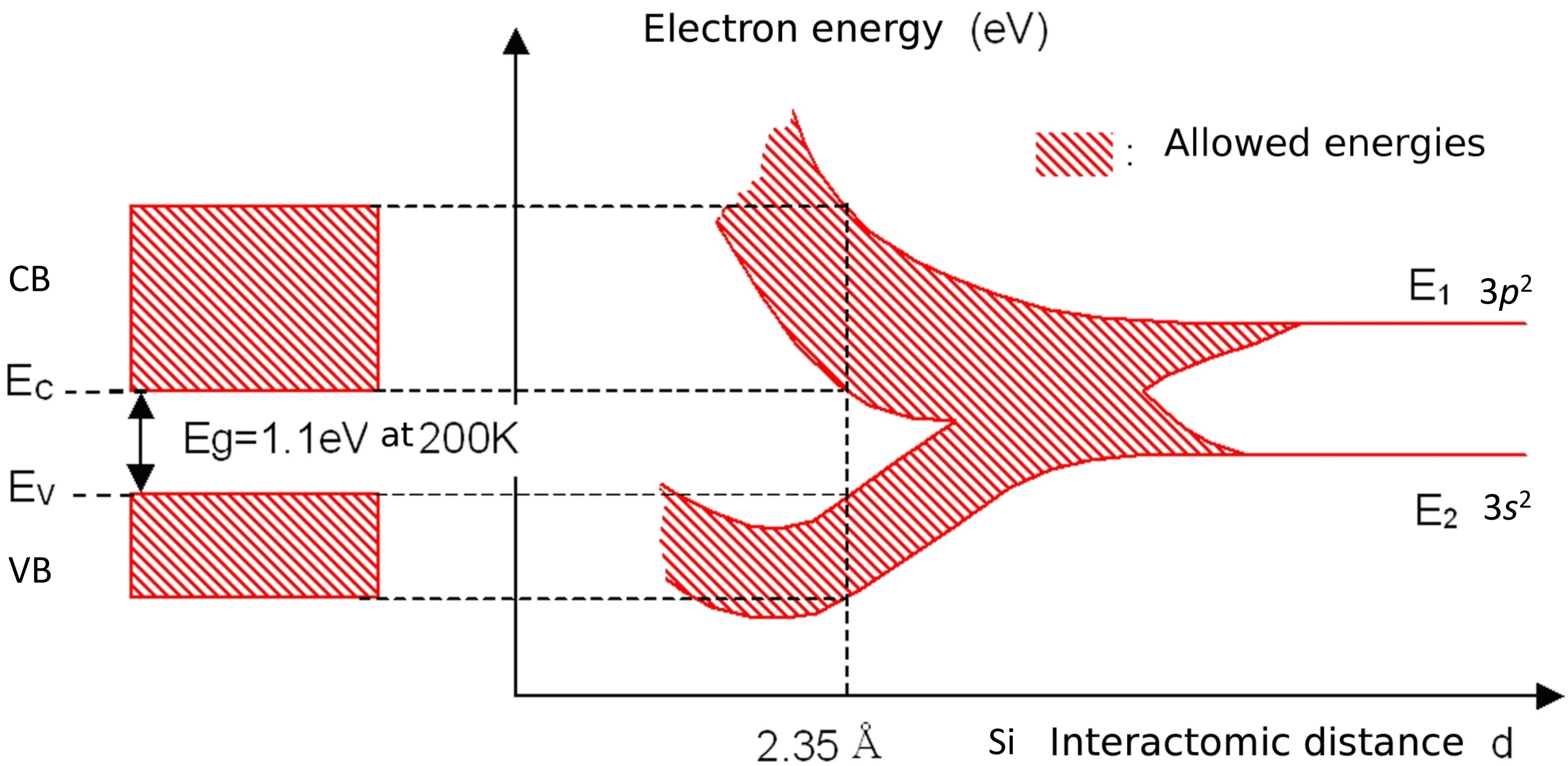


[Ne] $3s^2$ $3p^2$

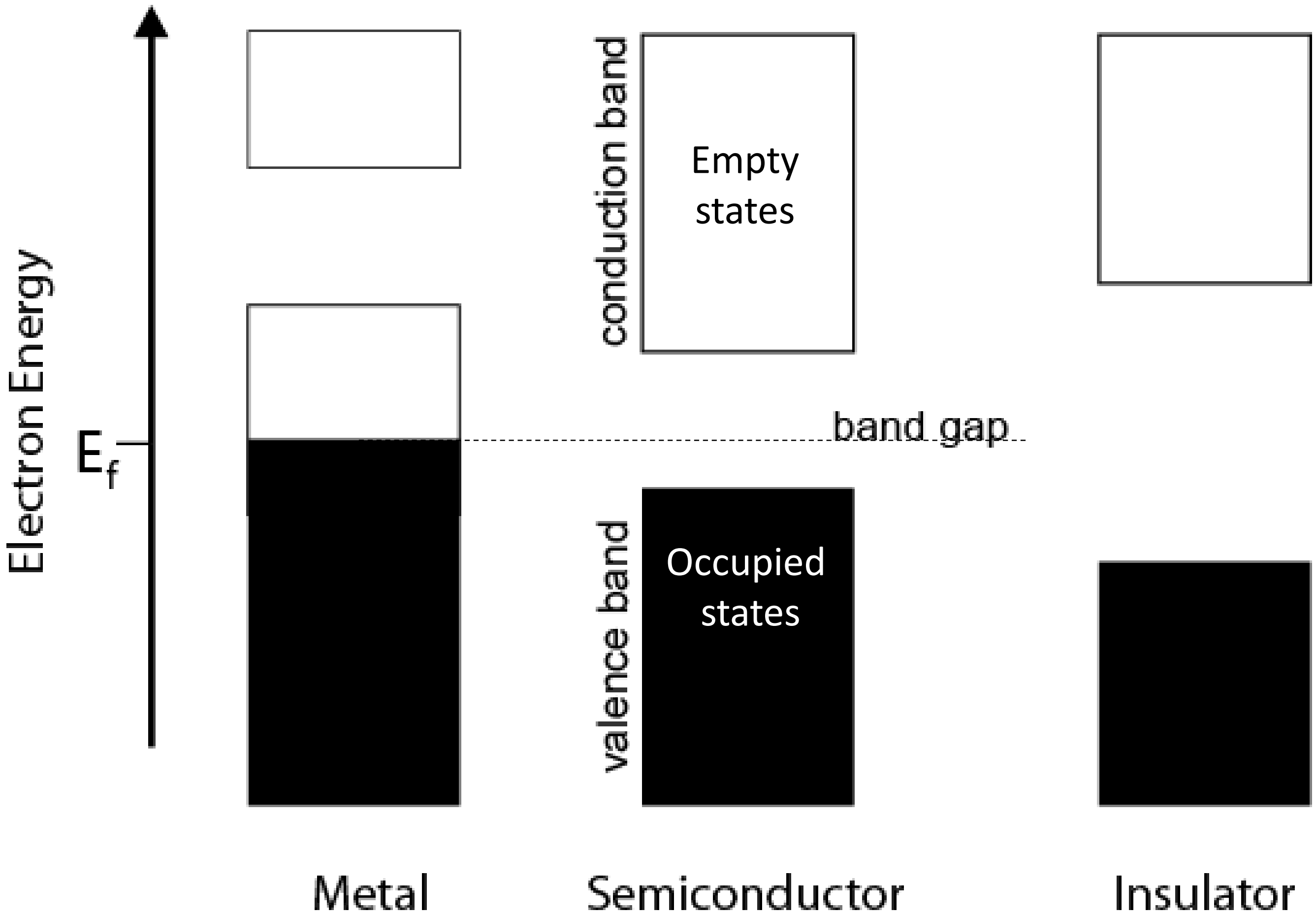


Model of a silicon crystal seen along the <100> direction.

Description of a semiconductor

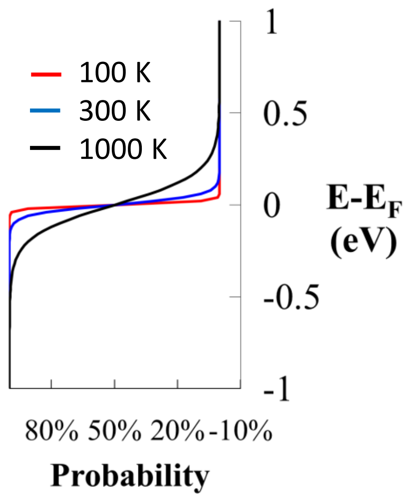


Description of a semiconductor



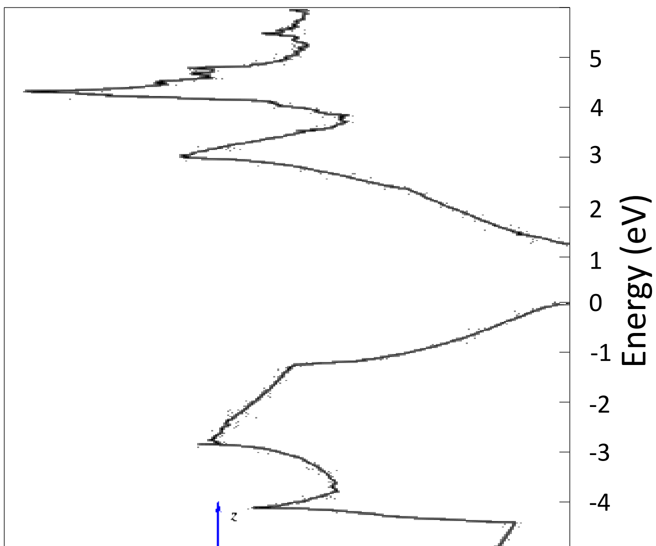
Distribution function for electrons:

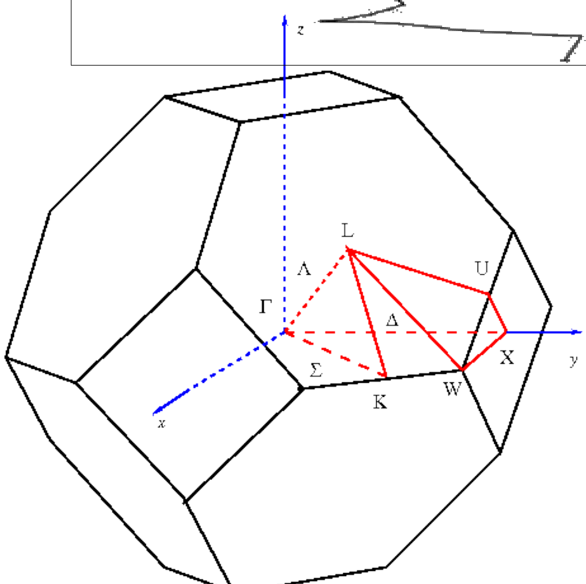
$$f(E_e) = \frac{1}{1 + exp\left(\frac{(E_e - E_F)}{k_B T}\right)}$$

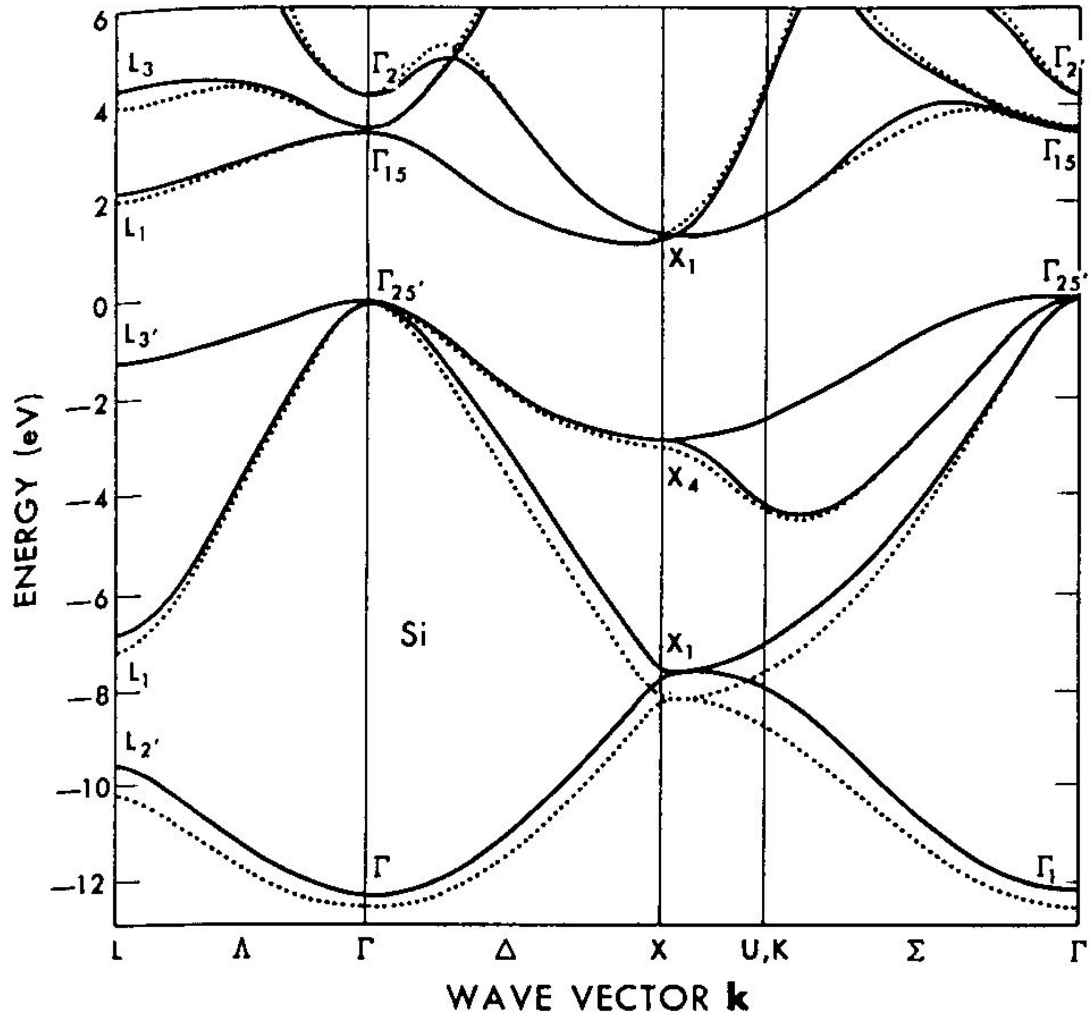


Band structure and density of states

Density of states

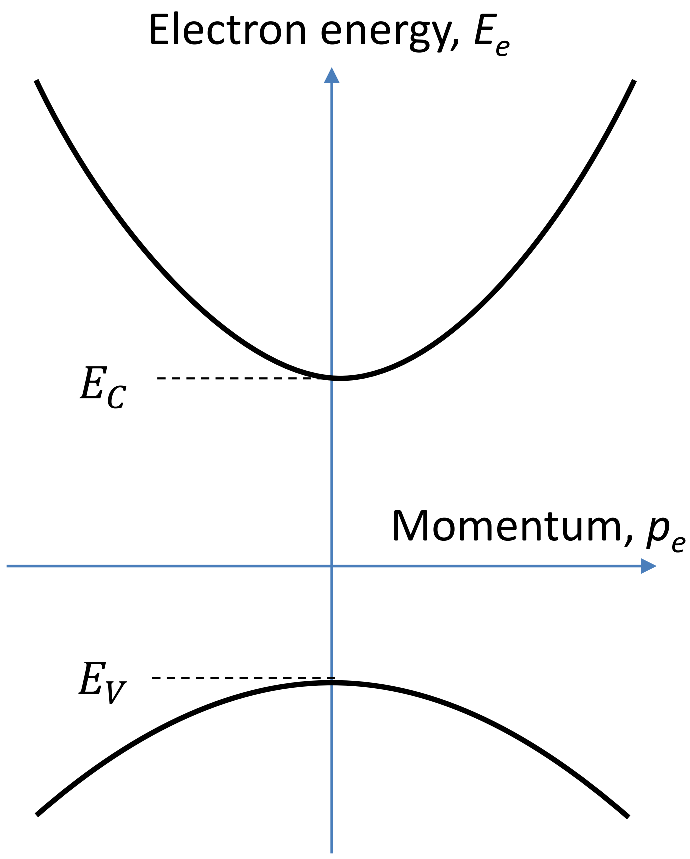






$$k = \frac{p}{\hbar} \text{ (momentum)}$$

Localized density of states as a function of energy



Number of states available for an electron in volume V:

$$N_e(|p_e|) = \frac{8\pi |p_e|^3 V}{3h^3}$$

Approximation of electron kinetic energy:

$$E_{e,kin} = E_e - E_C = \frac{|p_e|^2}{2m_e^*}$$

Density of states as a function of energy:

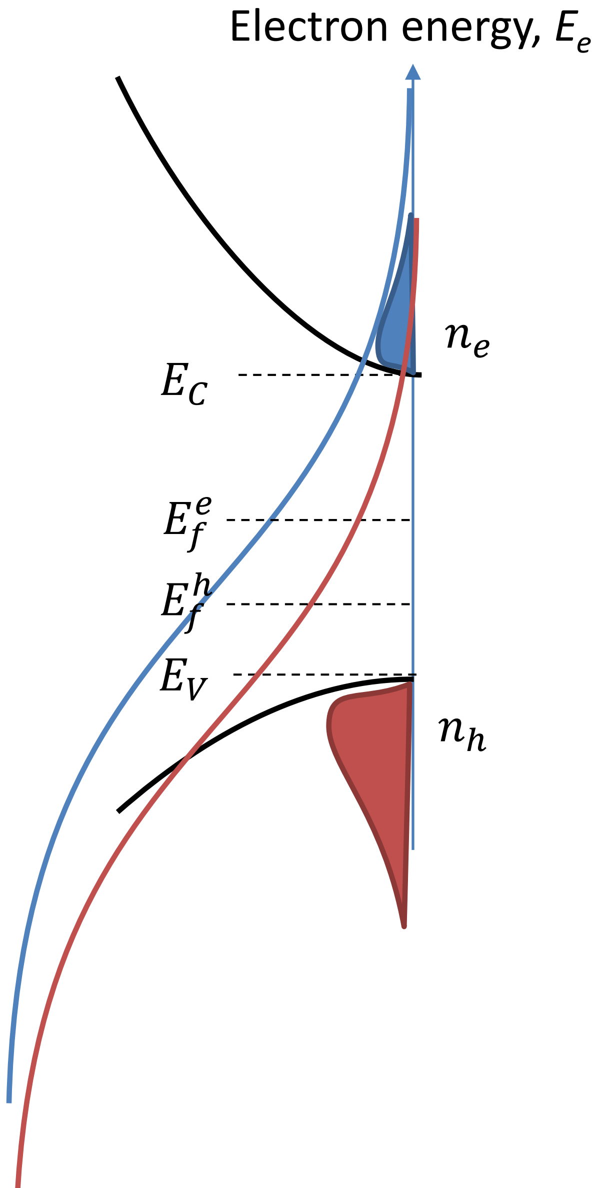
$$D_e(E_e) = \frac{1}{V}\frac{dN_e}{dE_e} = 4\pi \left(\frac{2m_e^*}{h^2}\right)^{3/2} (E_e - E_C)^{1/2}$$

The number of electrons in the conduction band:

$$n_e = \int_{E_C}^{\infty} D_e(E_e) f_e(E_e)\, dE_e = N_C\, exp\left(-\frac{E_C - E_f}{k_B T}\right)$$

$$N_C = 2\left(\frac{2\pi m_e^* k_B T}{h^2}\right)^{3/2}$$

Deviations from global equilibrium



Global equilibrium situations only:

The number of electrons in the conduction band:

$$n_e = N_C \, exp\left(-\frac{E_C - E_f}{k_B T}\right)$$

Similarly for holes:

$$n_h = N_V \, exp\left(-\frac{E_f - E_V}{k_B T}\right)$$

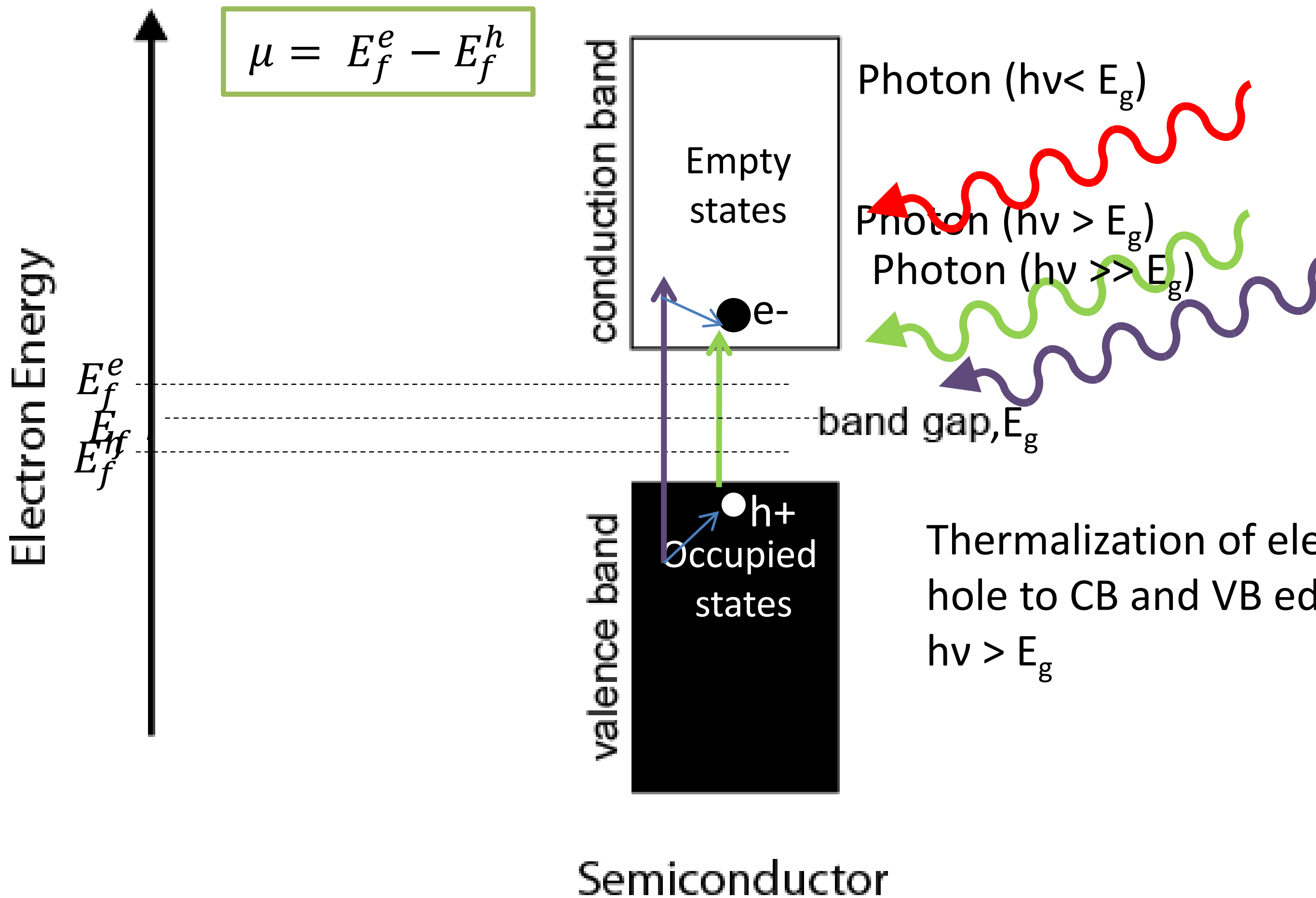
For non-equilibrium situations (globally) local equilibrium can be described:

$$n_e = N_C^{eff} exp\left(-\frac{E_C - E_f^e}{k_B T}\right)$$

Similarly for holes:

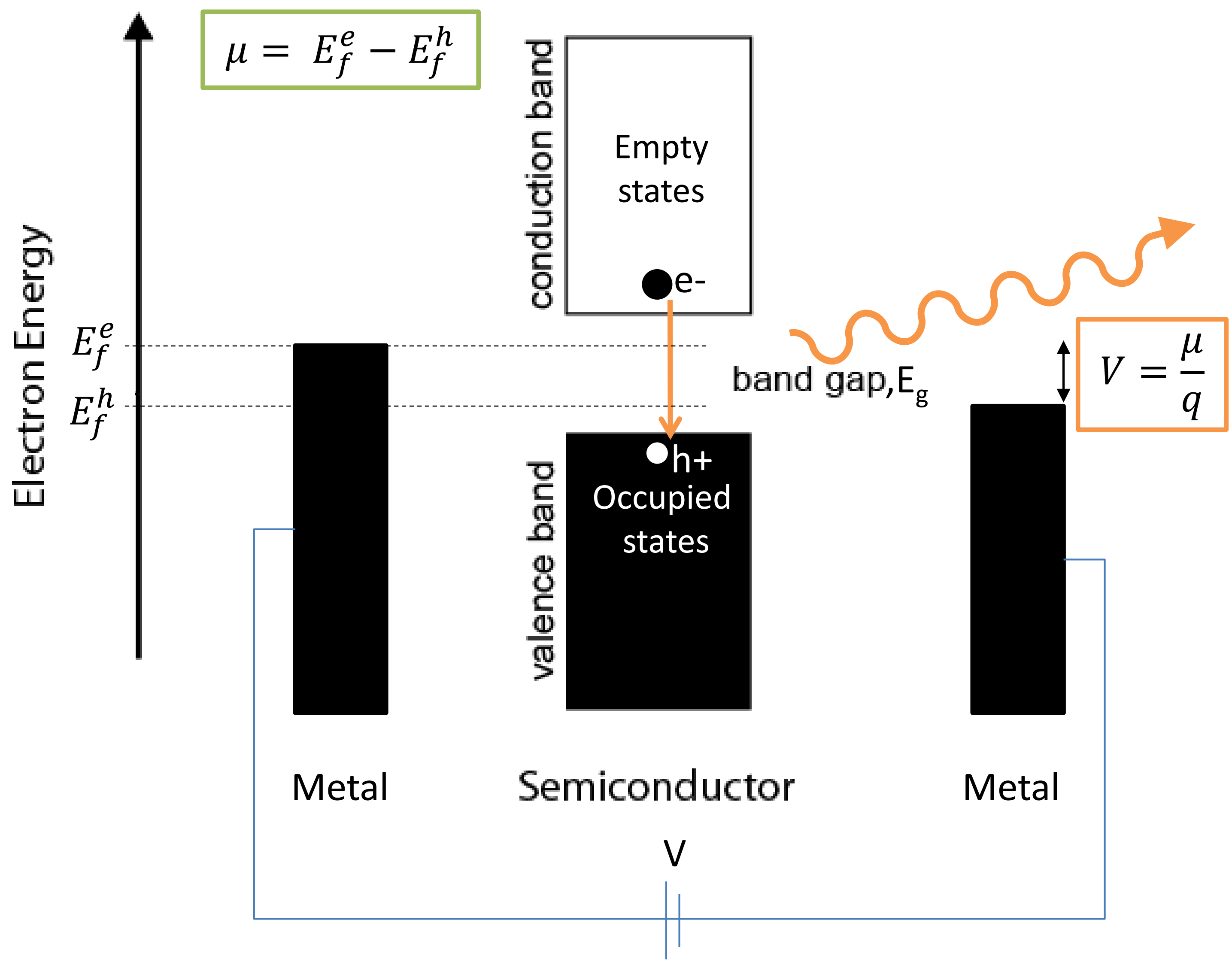
$$n_h = N_V^{eff} exp\left(-\frac{E_f^h - E_V}{k_B T}\right)$$

Description of a semiconductor



Thermalization of electron and hole to CB and VB edge when $h\nu > E_g$

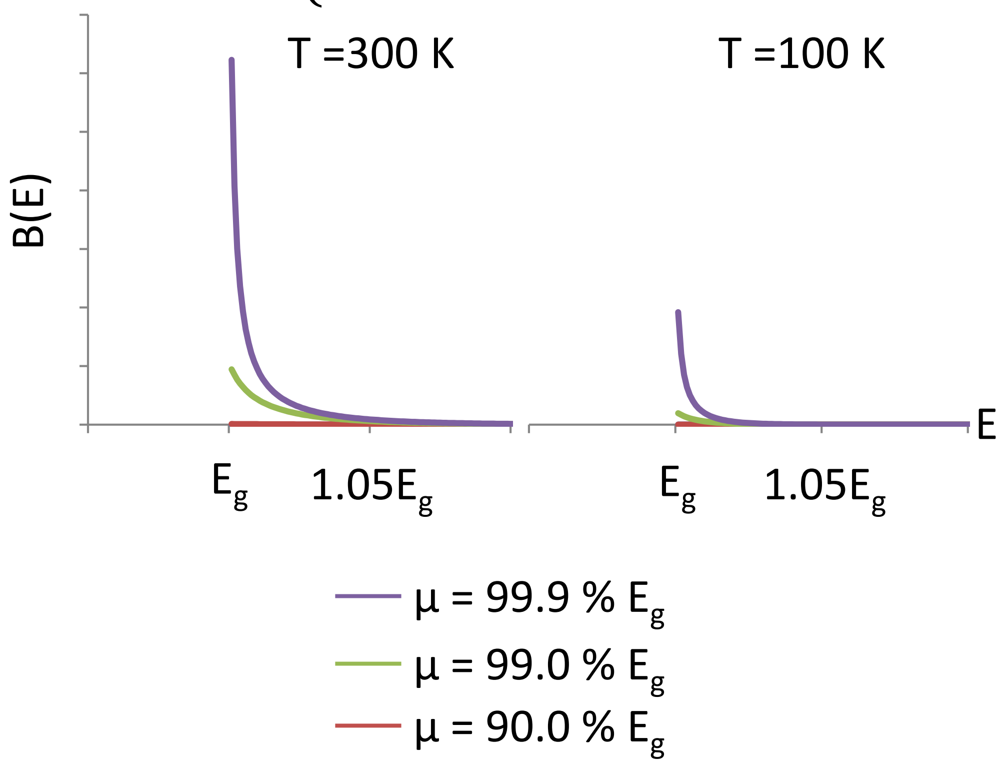
Description of a semiconductor



Emission from an ohmic diode

Emission spectrum from *an idealized* semiconductor (at Temp T and with a chemical potential μ)

$$B(E,T,\mu) = \begin{cases} 0 & for\ E \leq E_g \\ \dfrac{2\pi}{c^2 h^3} \dfrac{E^2}{exp\left(\dfrac{E-\mu}{k_B T}\right) - 1} & for\ E > E_g \end{cases}$$

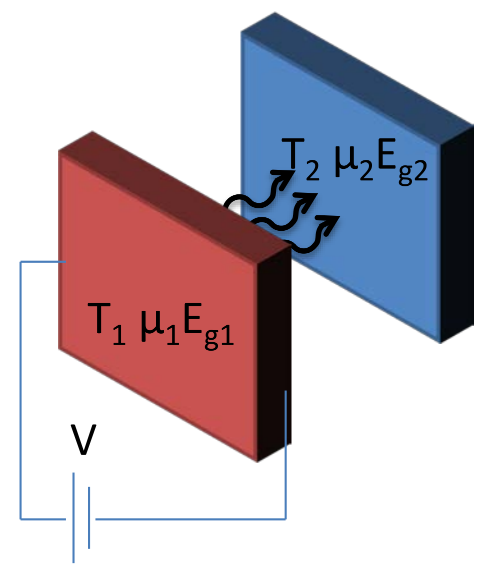


Total Number of photons emitted per unit area:

$$\Phi(T,\mu,E_g) = \int_{E_g}^{\infty} B(E)dE$$

Net electron flux through device:

$$J = -q\Phi$$



Photon exchange between biased semiconductors

Net photon Flux

$$\Phi = \int_{E_{g1}}^{\infty} B_1(E)dE - \int_{E_{g2}}^{\infty} B_2(E)dE = k\left[\int_{E_{g1}}^{\infty} \frac{E^2 dE}{exp\left(\frac{E-\mu_1}{k_B T_1}\right)-1} - \int_{E_{g2}}^{\infty} \frac{E^2 dE}{exp\left(\frac{E-\mu_2}{k_B T_2}\right)-1}\right] \qquad k = \frac{2\pi}{c^2 h^3}$$

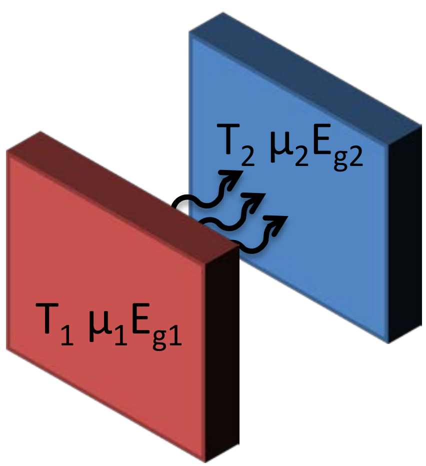
Net electron flux through device:

$$J = -q\Phi$$

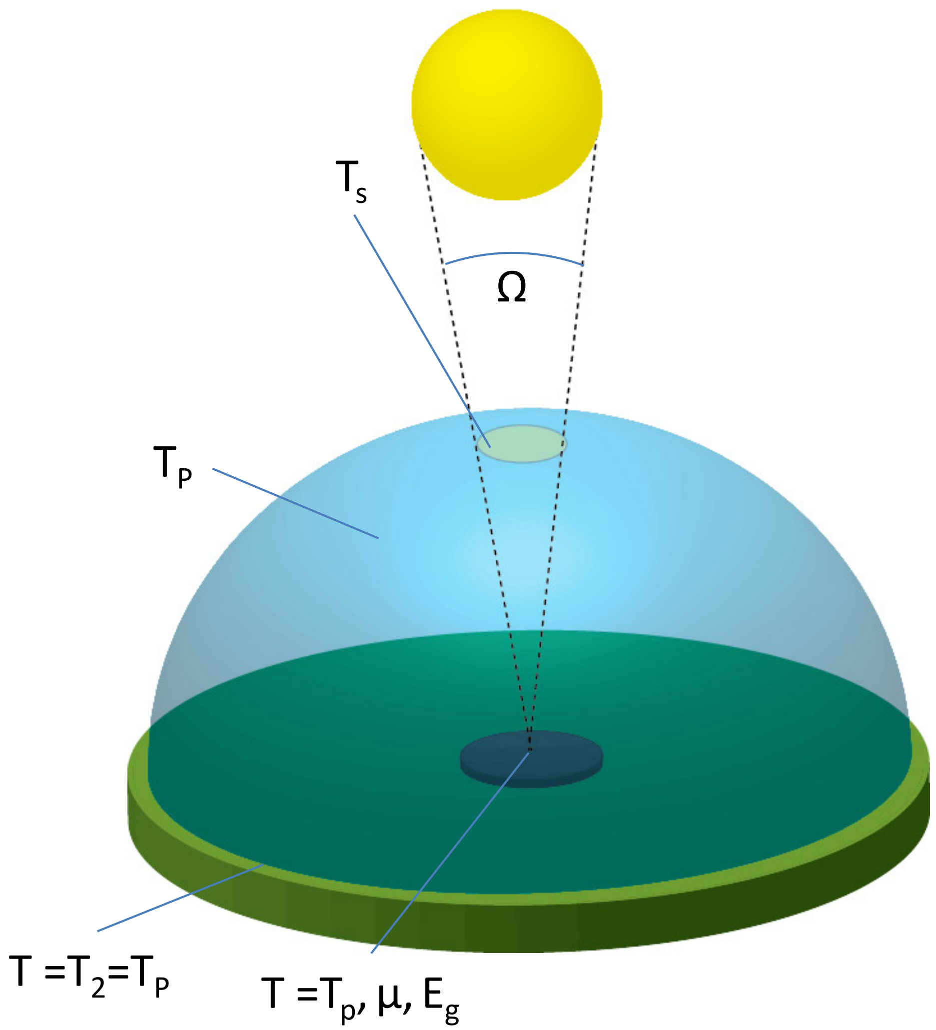
Recall that

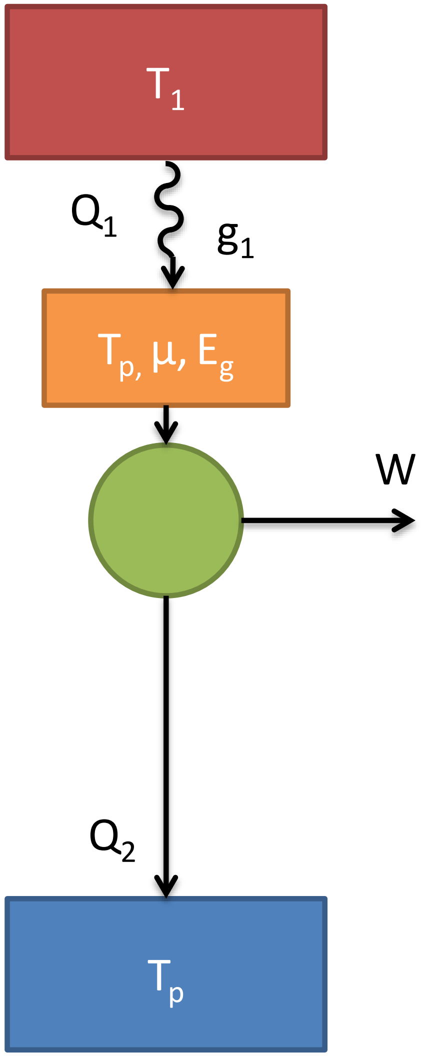
$$\mu = qV$$

$$J(V_1, V_2, T_1, T_2) = -q\Phi = -qk\left[\int_{E_{g1}}^{\infty} \frac{E^2 dE}{exp\left(\frac{E-qV_1}{k_B T_1}\right)-1} - \int_{E_{g2}}^{\infty} \frac{E^2 dE}{exp\left(\frac{E-qV_2}{k_B T_2}\right)-1}\right]$$



Building a photovoltaic device





Building a photovoltaic device

Net electron flux through device:

$$J = -q\Phi$$

Recall that

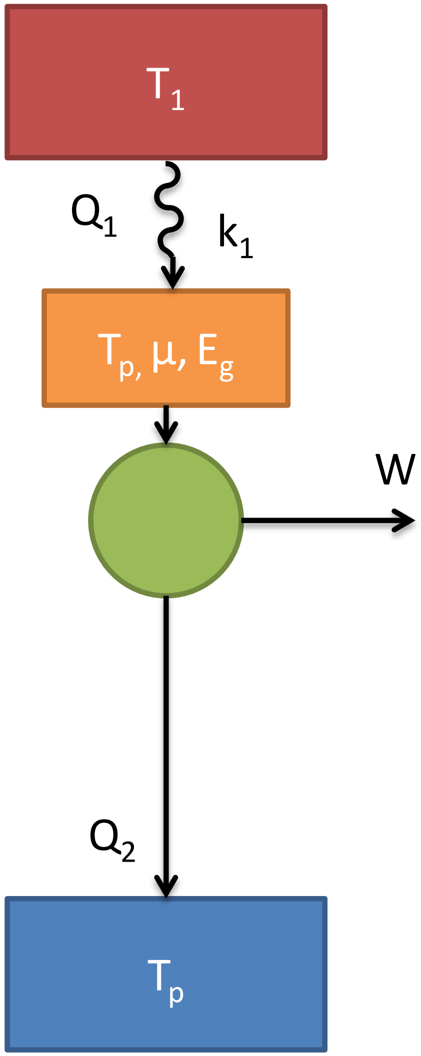
$$\mu = qV$$

Then:

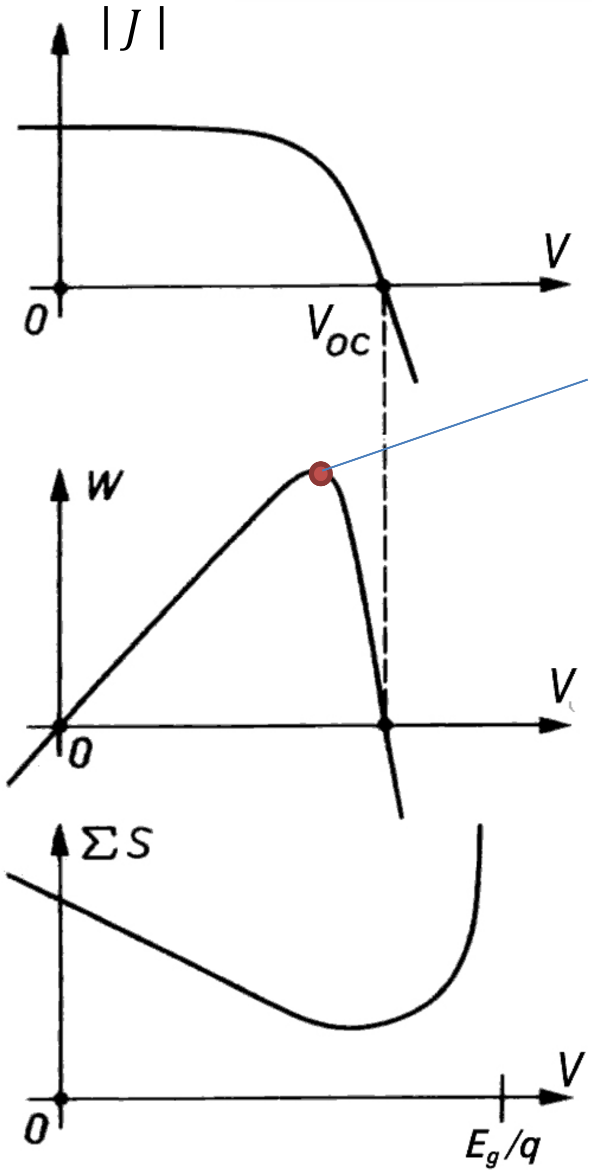
$$J(V) = -qk\left[Cf\int_{E_g}^{\infty}\frac{E^2 dE}{exp\left(\frac{E}{k_B T_s}\right) - 1}\right.$$

Also the electrical power can be defined:

$$W(V) = V|J(V)|$$



$$J(V) = -qk\left[Cf\int_{E_g}^{\infty}\frac{E^2dE}{exp\left(\frac{E}{k_BT_s}\right)-1} - (1-Cf)\int_{E_g}^{\infty}\frac{E^2dE}{exp\left(\frac{E}{k_BT_p}\right)-1} - \int_{E_g}^{\infty}\frac{E^2dE}{exp\left(\frac{E-qV}{k_BT_p}\right)-1}\right]$$



For $\frac{dW}{dV} = 0$

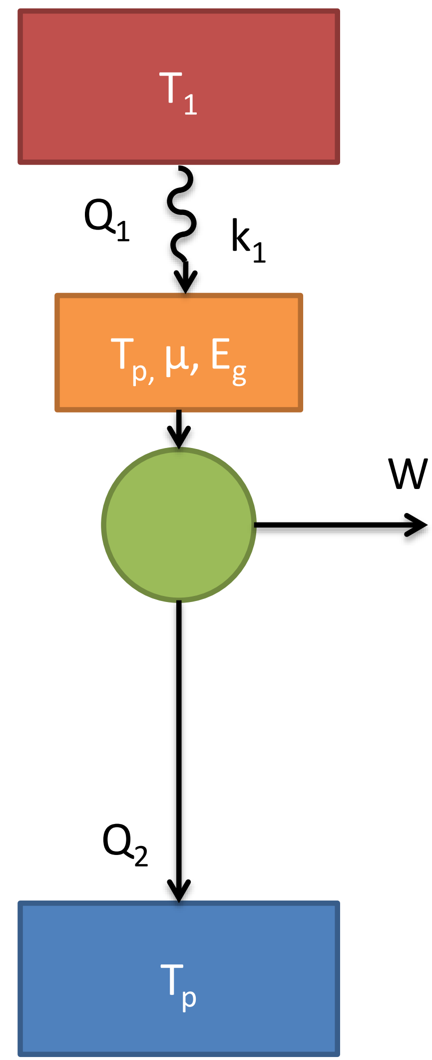
Depends on $\frac{T_p}{T_s}, Cf, E_g$

Solar energy efficiency:

$$W = VJ(V) = \eta_{solar} Cf\sigma T_s^4$$

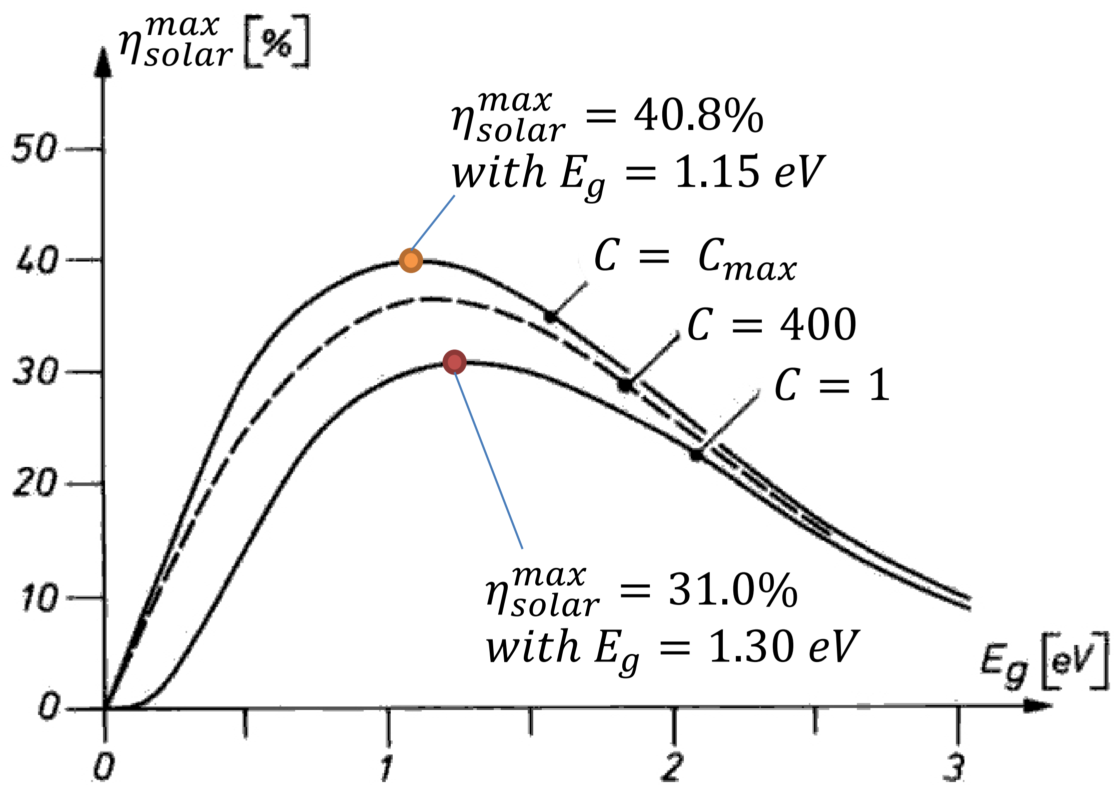
$$\eta_{solar} = \frac{VJ(V)}{Cf\sigma T_s^4}$$

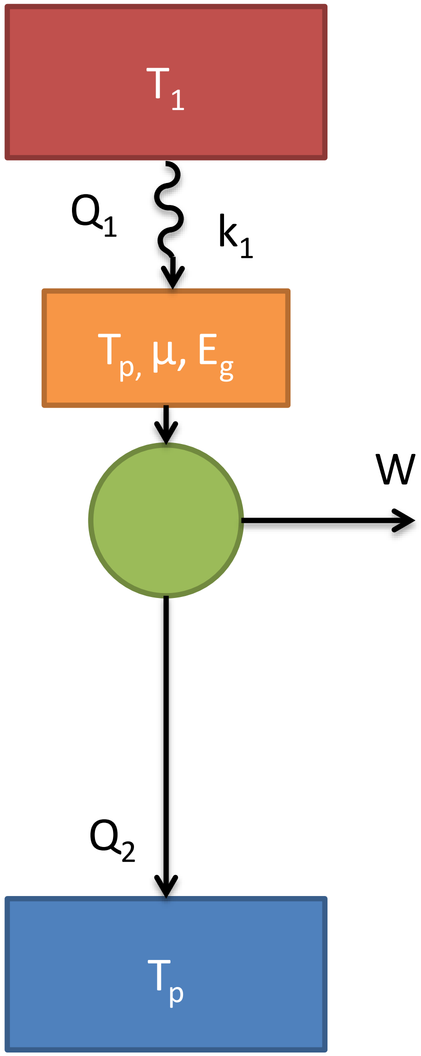
$$\eta_{solar}^{max} = \frac{[VJ(V)]_{\frac{dVJ(V)}{dV}=0}}{Cf\sigma T_s^4}$$



Building a photovoltaic device

Maximum solar energy conversion efficiency for planet earth with a semiconductor of band gap E_g

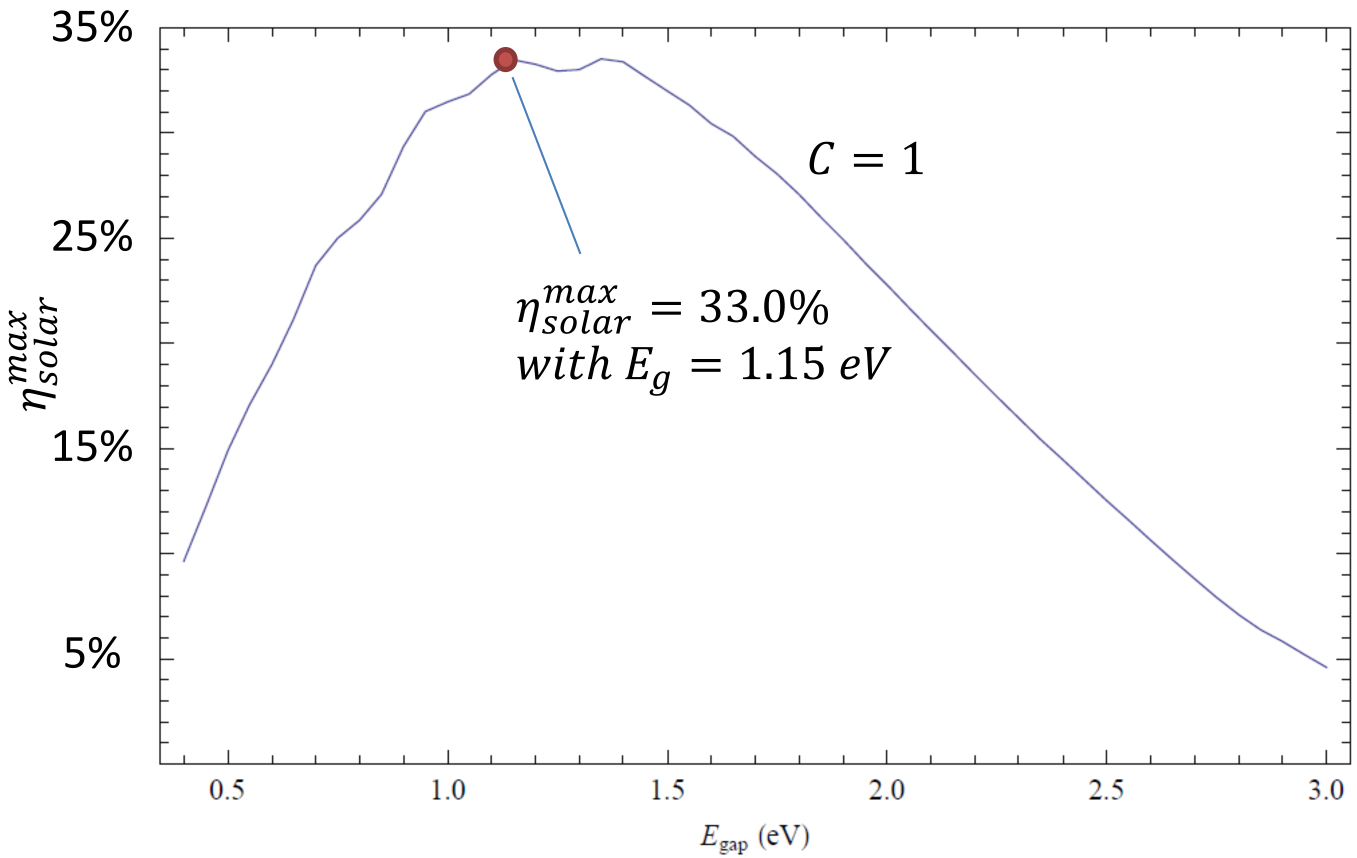


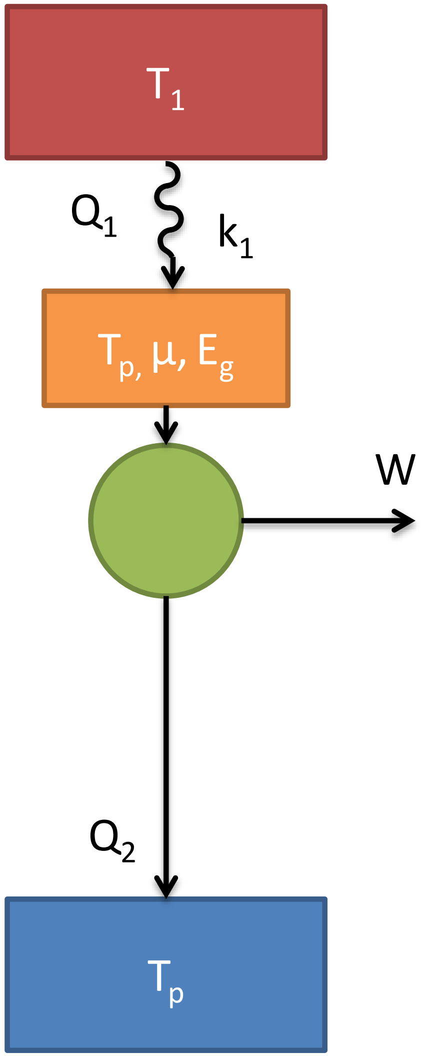


Building a photovoltaic device

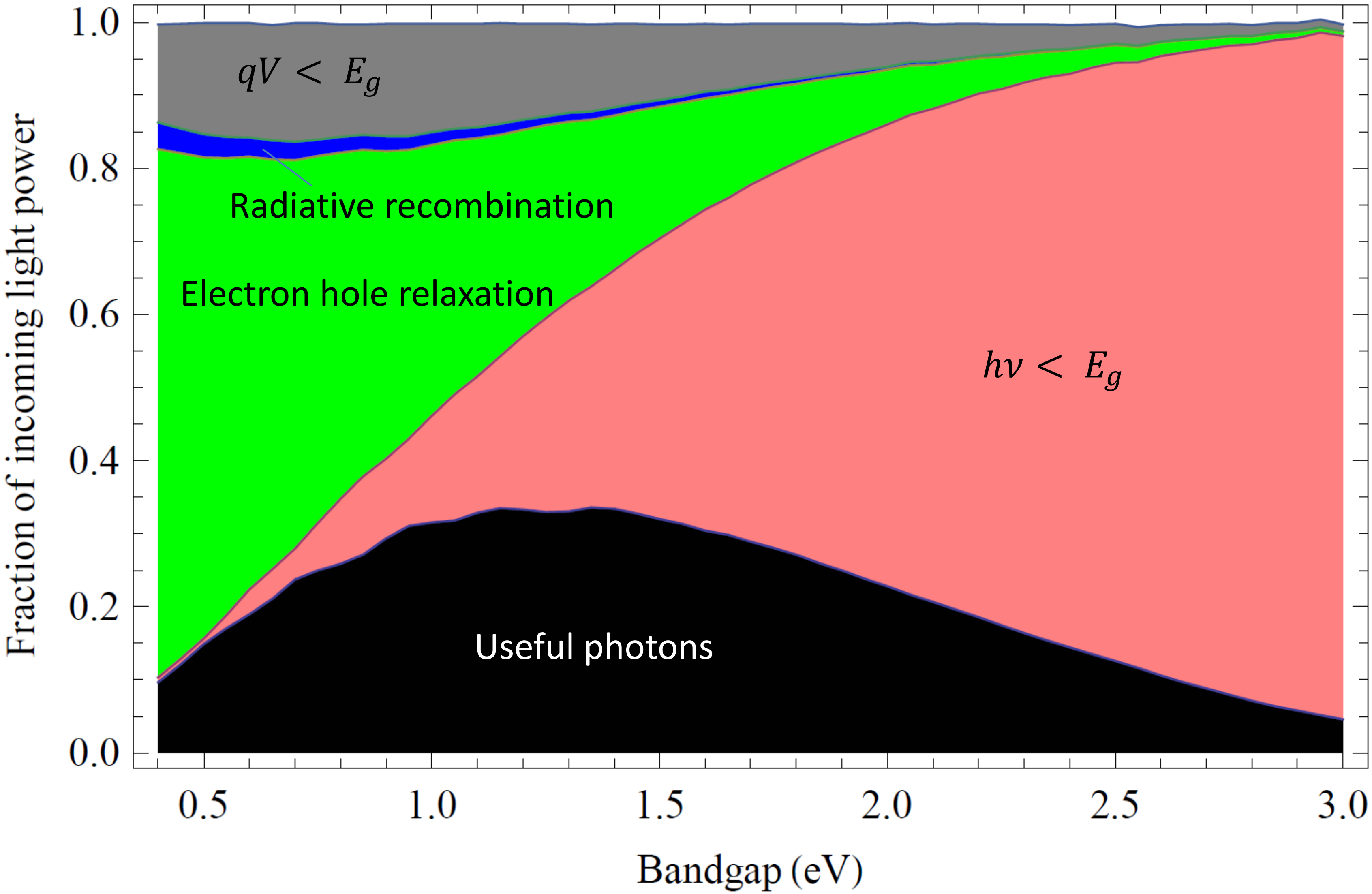
Maximum solar energy conversion efficiency for planet earth with a semiconductor of band gap E_g

With the standard solar spectrum

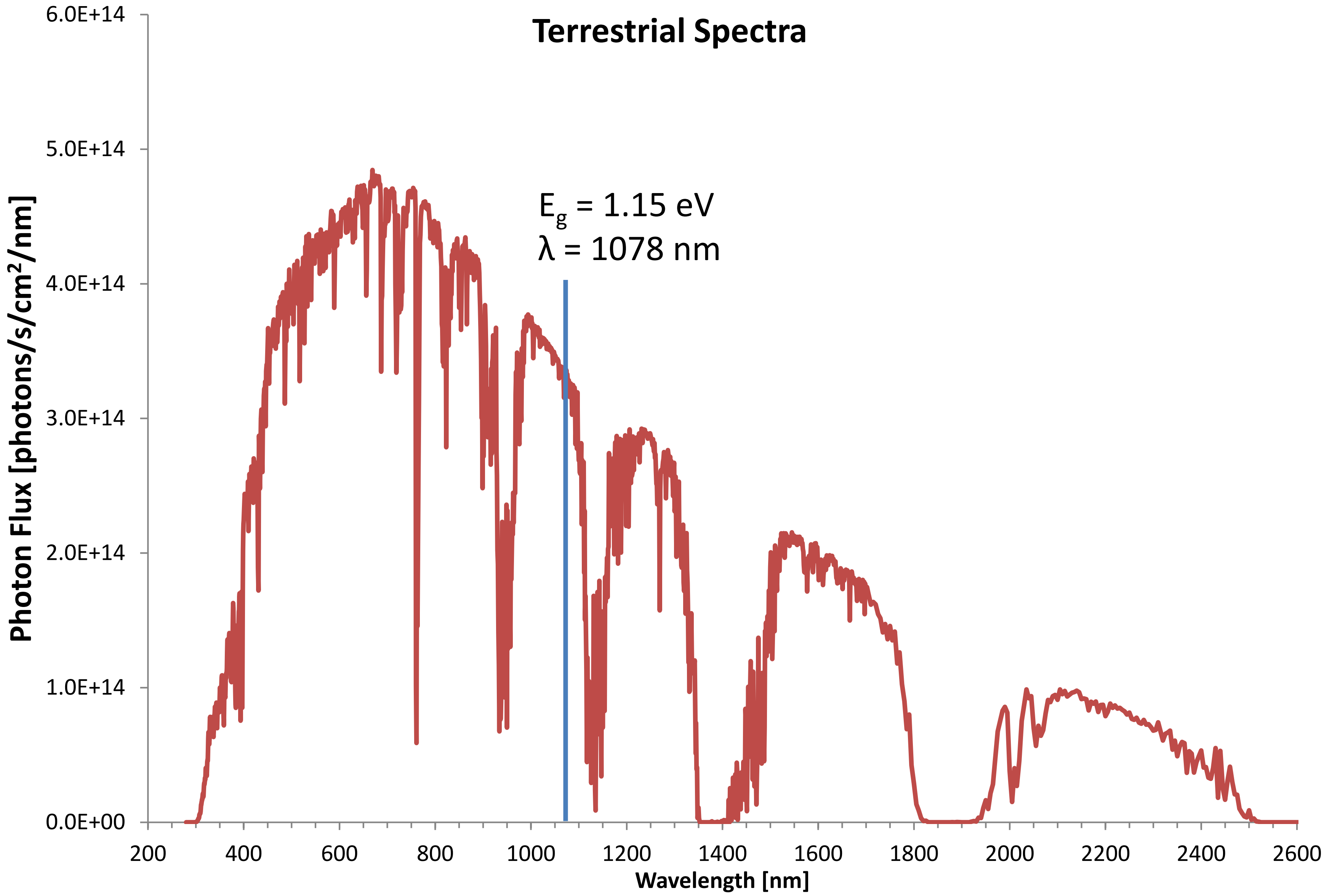




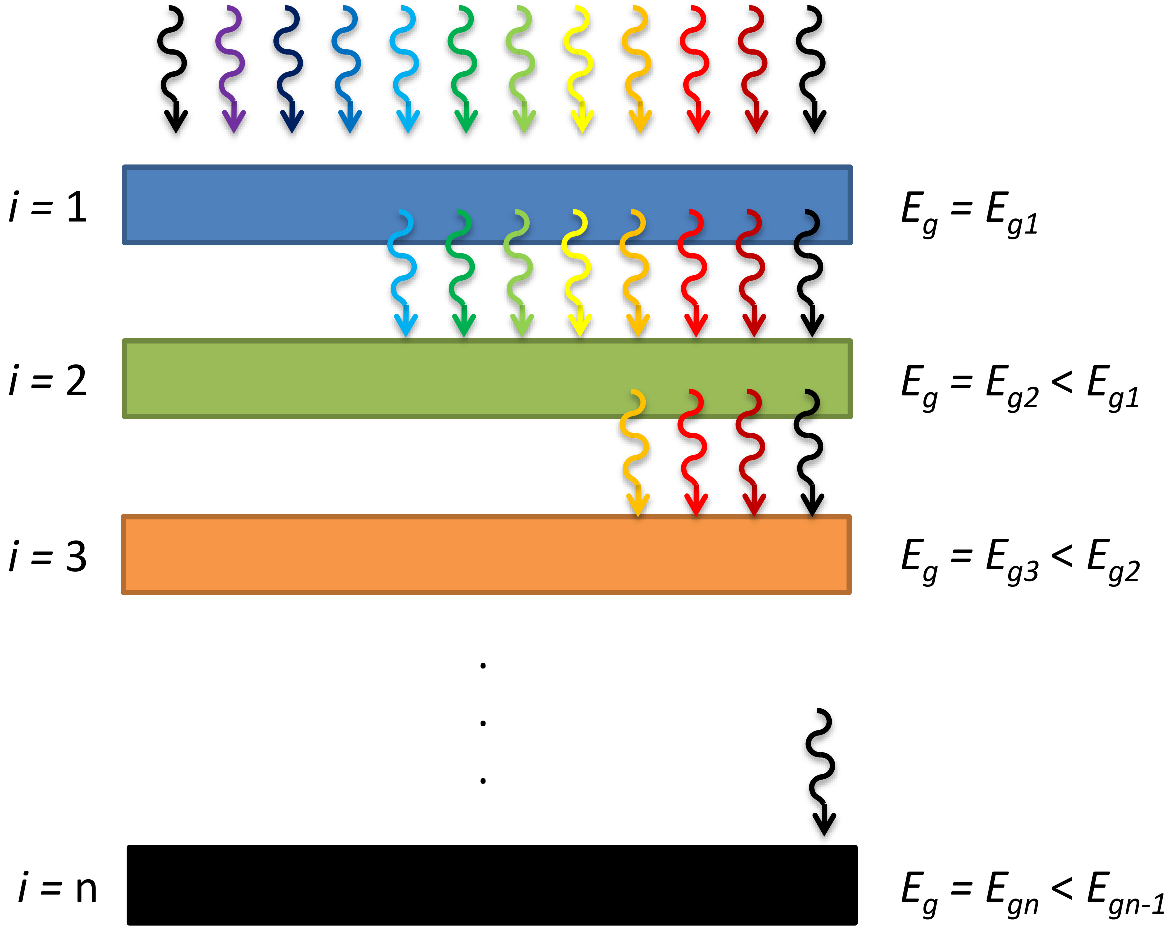
Losses in semiconductor solar cells



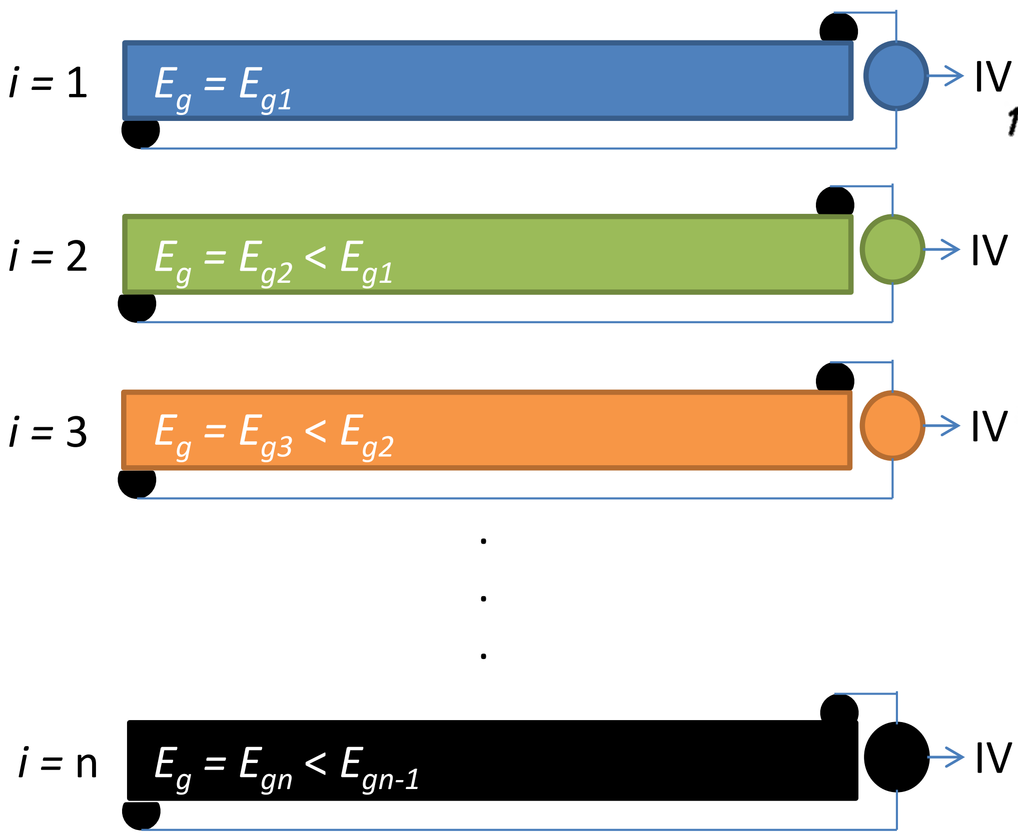
Single absorber conversion

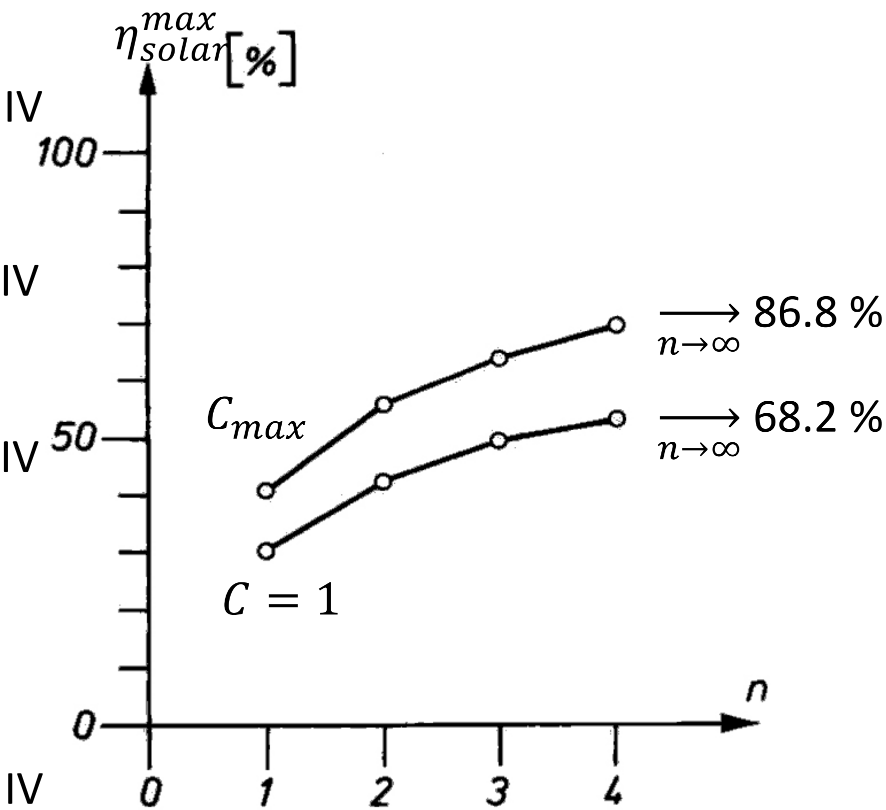


Multi“color” conversion



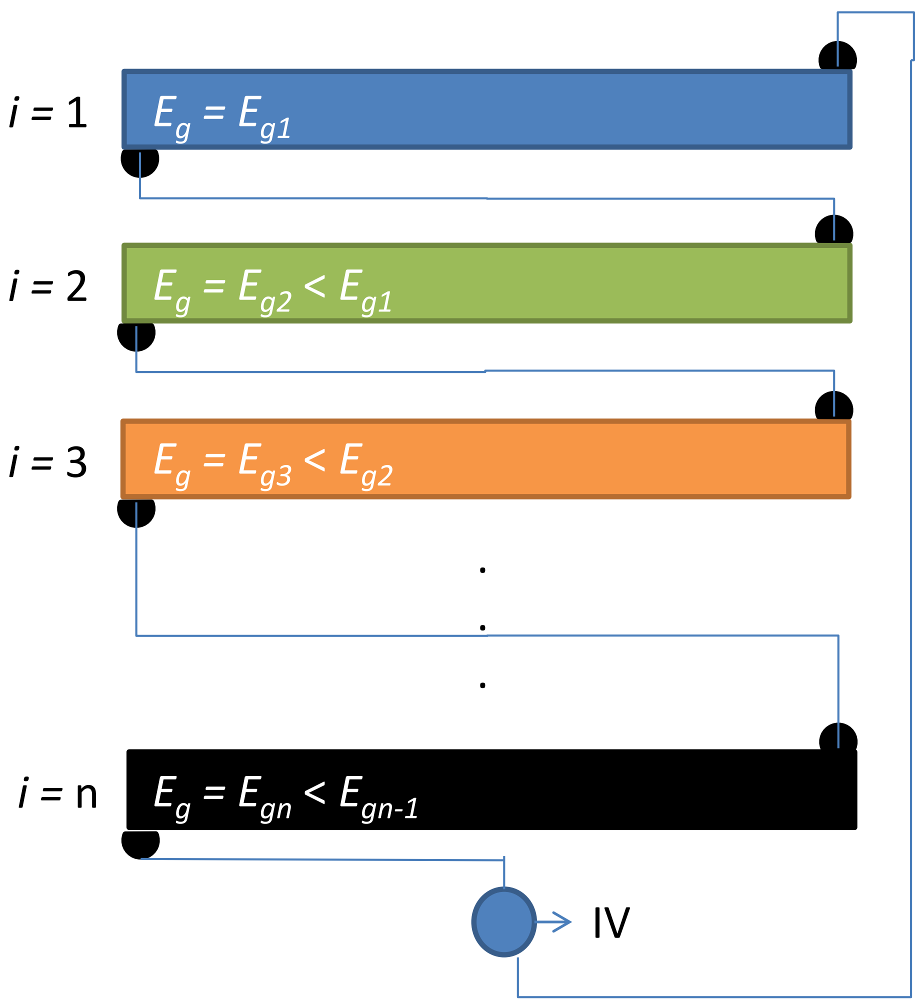
Multi“color” conversion

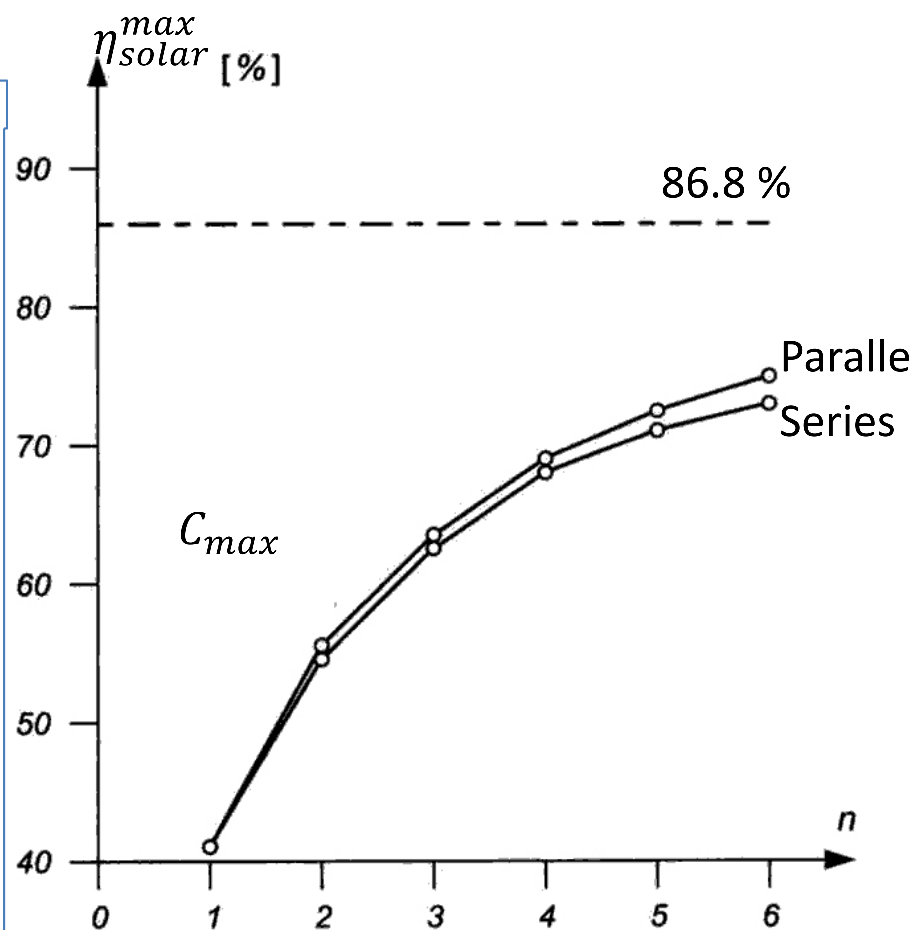




Multi“color” conversion

A more practical way to connect devices:





Individual cell characteristics

Connection	Independent Band gaps (eV)	Independent Max. efficiency	Series Band gaps (eV)	Series Max. efficiency
n = 1	1.06	40.6	1.06	40.6
n = 2	1.63		1.49	
	0.74	55.6	0.74	55.3
n = 3	2.02		1.75	
	1.21		1.10	
	0.59	63.6	0.58	63.0
n = 4	2.31		1.94	
	1.55		1.34	
	0.99		0.90	
	0.50	68.5	0.49	67.7

I. Tobias, A. Luque, *Prog. Photovolt: Res. Appl*. **2002**; *10*:323–329

Summary of photovoltaic conversion limits

- Semiconductors are special because they can have local equilibriums (within bands) and global imbalance (between bands)
- This property leads to the concept of quasi Fermi levels and a “chemical potential”
- Creating a simple diode device and investigating in the framework of a photovoltaic device gives us the “Shockley–Queisser limit” for solar energy conversion by a photovoltaic device
- Higher solar energy conversion can be achieved by using “multicolor” converters.

ChE 600 presentations for course credit

- PowerPoint (or equivalent) based presentation
  - *In groups of two* – 20-25 min total
- Focused on one of the publications provided
- Your presentation should contain:
  - Extensive background/motivation for the work
    - Introduce the general field (e.g. hot carrier cells, or, 2D semiconductors, etc…)
    - Summarize previous main results in that general field.
    - Clearly define the motivation for the paper and hypothesis tested
  - Describe the concept/methodology/results in detail
  - Critically comment on the work
    - Significance of the result and impact on the field
    - Other similar/competing approaches?
  - Follow-up work needed (or already performed) to fulfill the promise of the concept