Photovoltaik (2)

Basic Principles of Photovoltaics
Maximum power conversion of photovoltaic devices

Ressources:
Peter Würfel, Physik der Solarzellen
Jenny Nelson, The Physics of Solar Cells
Thomas Dittrich, Material Concepts for Solar cells & lecture notes

Übersicht der Vorlesung

15.09.2015	allg. Einführung in die Solarenergie
22.09.2015	Basic Principles of Photovoltaics
29.09.2015	Electrons and Holes in Semiconductors
6.10.2015	Absorption, Recombination, and Generation
13.10.2015	The ideal semi-infinite pn-junction
20.10.2015	Illuminated pn-junction
27.10.2015	c-Si solar cells
3.11.2015	Basics of thin film solar cells
10.11.2015	Thin film solar cells
17.11.2015	Concepts of nanostructured solar cells
24.11.2015	Dye Sensitized Solar Cells
1.12.2015	Exkursion?
8.12.2015	
15.12.2015	**Prüfung**

The sun is a hot fire ball

spectrum of the black body radiation (Planck)
(energy flux as a function of the photon energy and of the temperature)

with
h = 6.6 10^{-34} Js
c = $3 \cdot 10^{8}$ m/s
k_B = 1.38 10^{-23} J/K

$$E_{ph} = h \cdot \nu \qquad \frac{dJ_S(h\nu)}{d(h\nu)} = \frac{8\pi}{h^3c^2} \cdot \frac{(h\nu)^3}{exp(\frac{h\nu}{k_BT_S}) - 1}$$

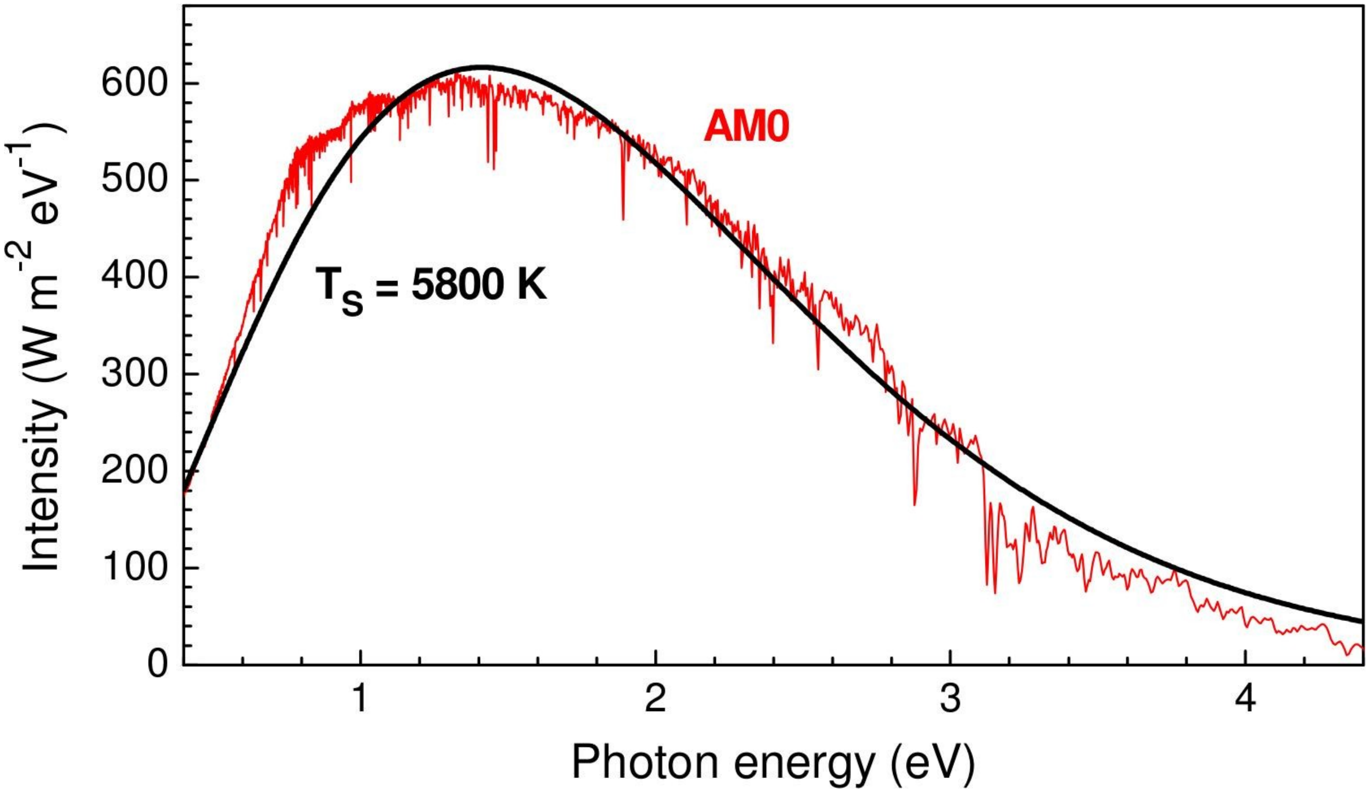
$$(h\nu)_{max} = 2.82 \cdot k_BT$$

By measuring the photon energy at the maximum of the sun spectrum T_s can be obtained.

temperature at the surface of the sun:

$T_S \approx$ 5800 K

Energy flux spectrum and photon flux



For example: $$dJ_S(1.2eV) \approx 550[\frac{W}{m^2 \cdot eV}]$$

Photon flux b_s $$b_S(1.2eV) \approx \frac{550}{1.2 \cdot 1.6 \times 10^{16} \cdot 10^4}[\frac{1}{cm^2 s}]$$

$$b_S(1.2eV) \approx 3 \times 10^{17}[\frac{1}{cm^2 s}]$$

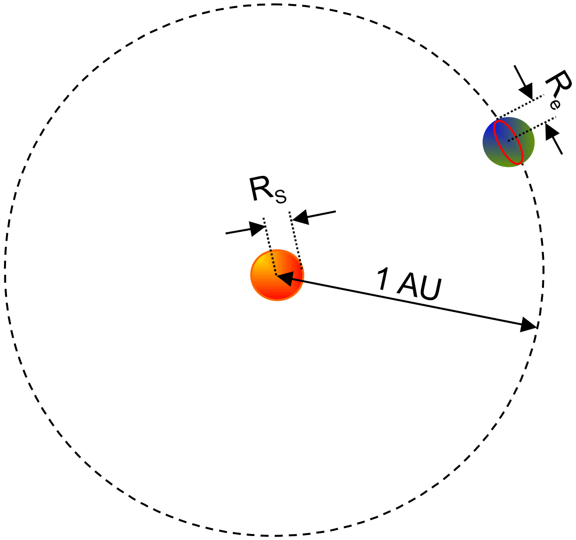
Power of the sun received on earth

Stefan-Boltzmann law $I_S = \sigma \cdot T^4$

power of the sun $P_S = \sigma \cdot T^4 \cdot 4\pi \cdot R_s^2$

power received on earth $P_e = P_S \cdot \frac{\pi \cdot R_e^2}{4\pi \cdot (AU)^2}$

with
$\sigma = 5.67\ 10^{-8}$ W/(m²K⁴)
$R_s = 7\ 10^5$ km
$R_e = 6.4\ 10^3$ km
$AU = 1.5\ 10^8$ km



$P_e \approx 1.8\ 10^8$ GW

more than 1000…10000 times
the energy demand of mankind

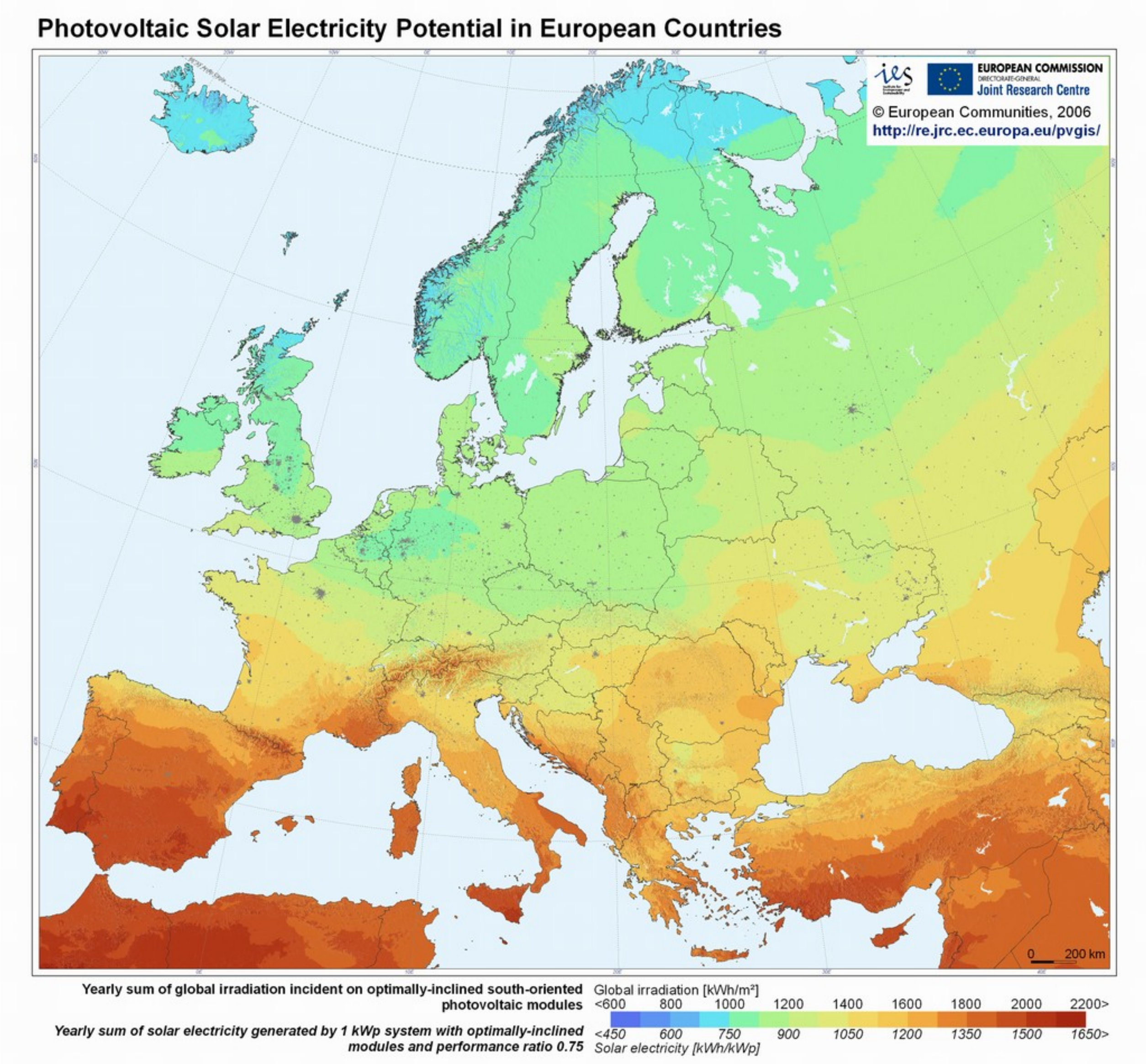
The solar constant

energy flux of sun light to the earth normalized to the area of 1 m²
Definition of the solar constant (J_S)

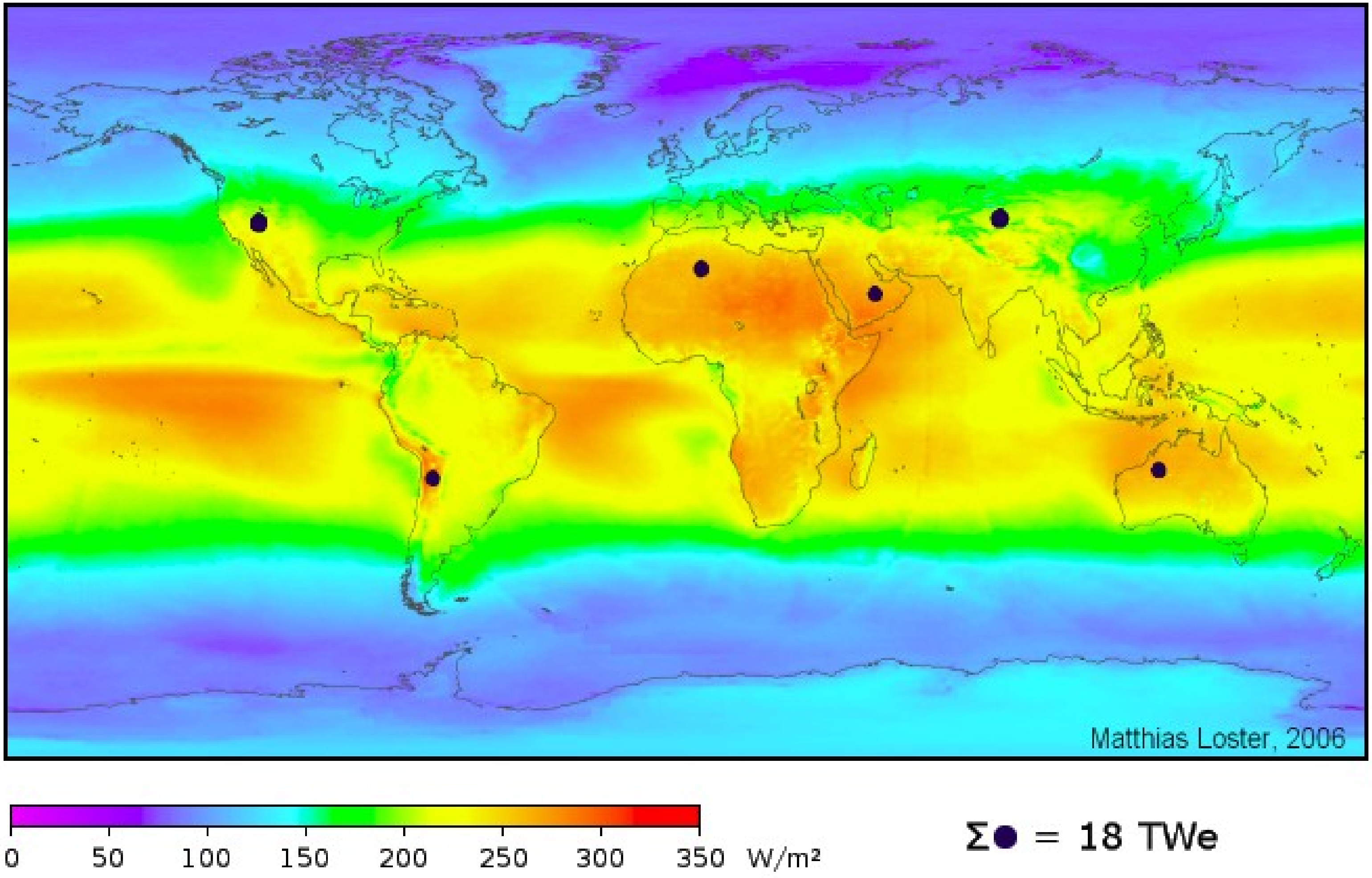
$$J_S = \frac{P_s}{4\pi \cdot (AU)^2}$$

J_S = 1356 W/m²

Insolation - Solar Irradiance



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



- three-year average of solar irradiance, including nights and cloud coverage
- area of black discs allows to achieve 18TW electrical power
- Global average: Extraterrestrial $<J_E>=1/4 \cdot 1356\ \mathrm{W/m^2}=339\ \mathrm{W/m^2}$

CH: 115 W/m^2 Saudi-Arabien: 285 W/m^2

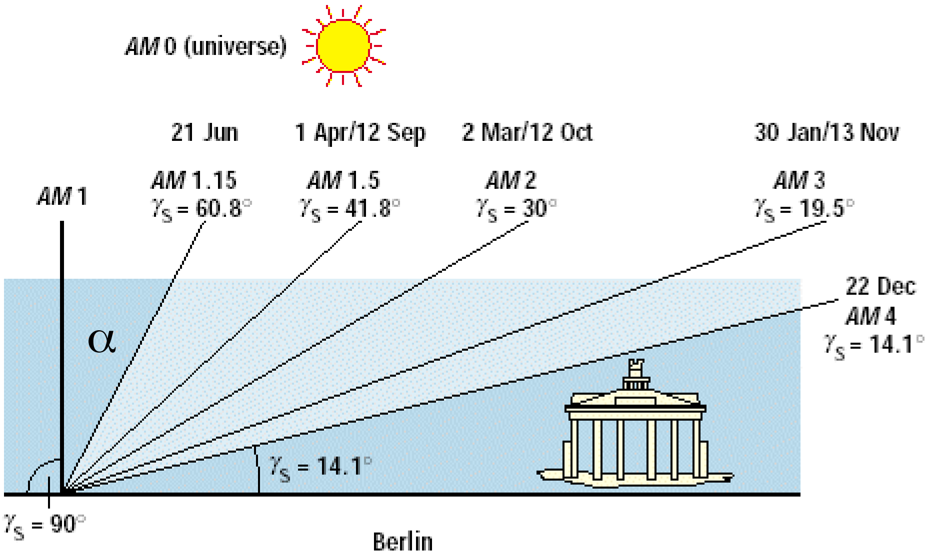
http://www.ez2c.de/ml/solar_land_area/

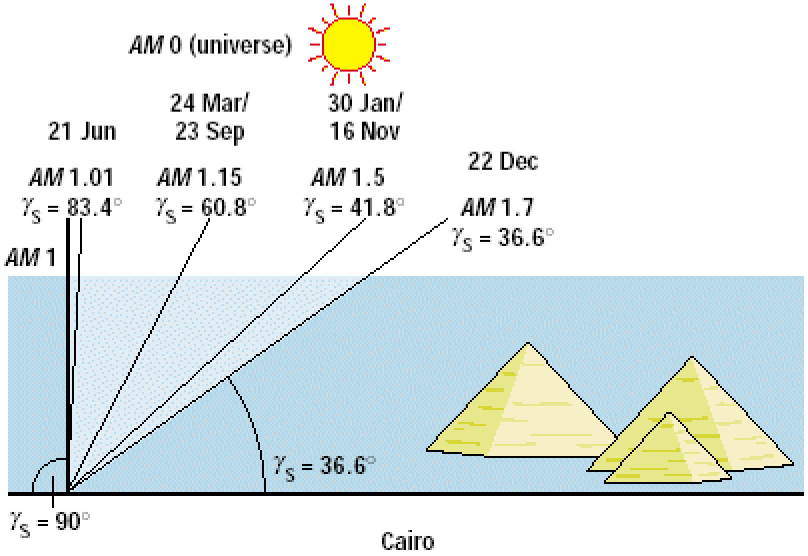
The role of the earth atmosphere

absorption of light by molecules
(H_2O, CO_2, O_2, O_3, N_2…)
heating of atmosphere
decrease of the intensity of sun light on ground

light scattering
(particles and molecules)
change of the direction of light

Air Mass: AM1.5, AM1.0….





Definition: For convenience AM1.5 is defined as 1000W/m^2 integrated irradiance

(Typical experimental values at 42º are 900W/m^2)

AM0: Extraterrestrial
AM1.0: equator

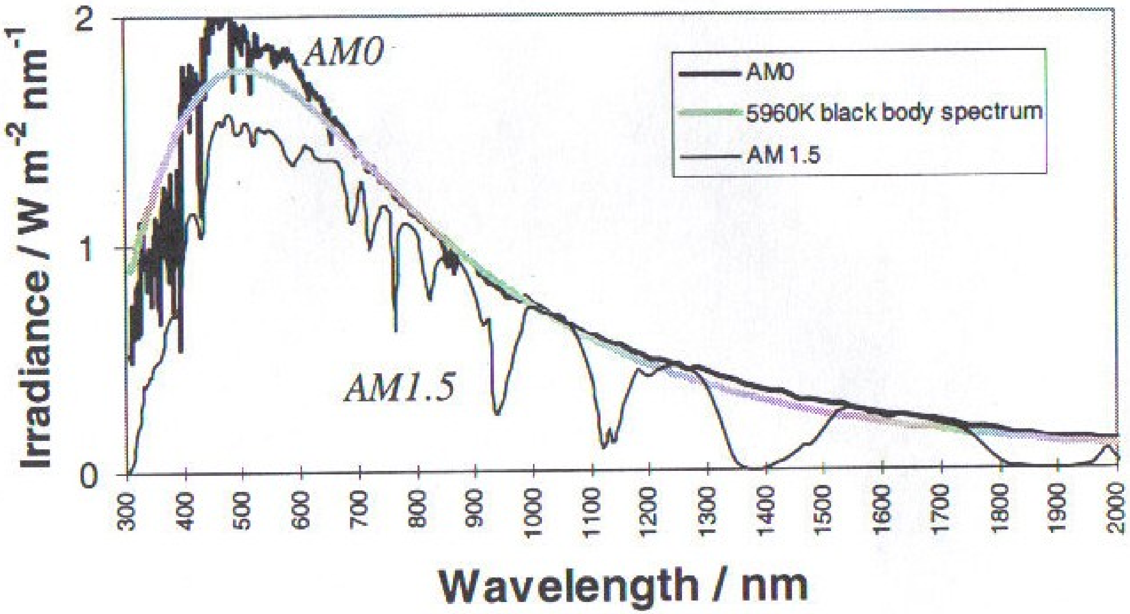
$$n_{AM} = \frac{1}{\sin(\gamma_S)}$$

$$\gamma_S = 41.8 \Rightarrow n_{AM} = 1.5$$

Alternatively: $n_{AM}) \frac{1}{\cos(\alpha)}$

http://www.volker-quaschning.de/articles/fundamentals1/index.php

Solar spectrum



- Comparison of AM0 (extraterrestial) with black body radistaion of T=5960K and AM 1.5
- Dips in spectrum at 900, 1100, 1400 and 1900nm (H_2O) and at 1800 and 2600nm (CO_2)

Temperature on earth from energy balance

$I_{atm} \rightarrow 0$

Energy flux from sun to earth

$$I_s = J_s \cdot \pi \cdot R_e^2$$

Black body radiation from earth into free space

$$I_e = \sigma \cdot T_e^4 \cdot 4\pi \cdot R_e^2$$

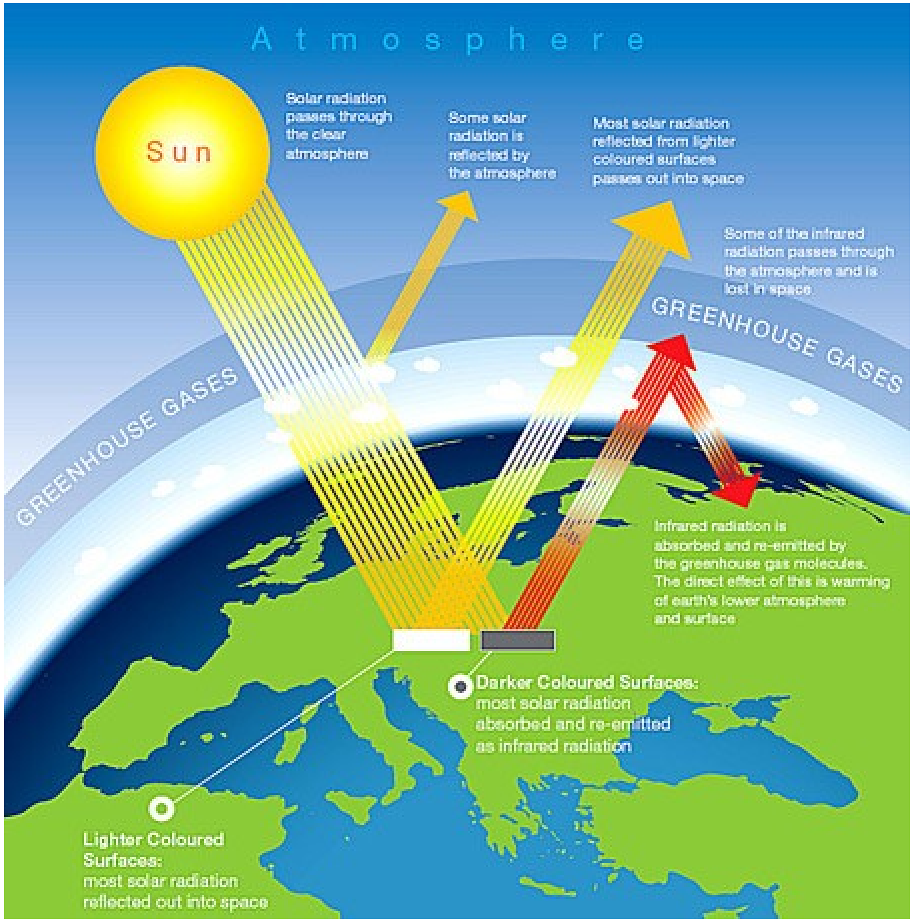
with
$\sigma = 5.67\ 10^{-8}\ \mathrm{W/(m^2K^4)}$
$J_s = 1.35\ \mathrm{kW/m^2}$

Balance

$$I_e = I_s$$

$$\Rightarrow T_e = \sqrt[4]{\frac{J_s \cdot \pi \cdot R_e^2}{\sigma \cdot 4\pi \cdot R_e^2}} \approx 277\ K$$

The Albedo effect, diffuse reflection



Albedo (or reflection coefficient) is the percentage of incoming radiation reflected off a surface.

http://www.ecocem.ie/environmental,albedo.htm

Temperature on earth with max green house effect

Assumption: the black body irradiation of the earth is absorbed completely by GHG (CO_2, CH_4,…) and half of this energy is re-absorbed by earth

Energy balance between earth atmosphere and free space

$$I_s = I_{atm} / 2$$

Energy balance on the earth

$$I_e = I_s + I_{atm} / 2$$
$$\Rightarrow \; I_e = 2 \cdot I_s$$

$$T_e = \sqrt[4]{2} \cdot 277\,K \approx 326\,K$$

Conversion of sun light

heating of rocks
radiation energy turns directly into entropy

heating of oceans and atmosphere
partial conversion into free energy (wind, hydropower)

photosynthesis
storage of free energy as chemical energy
coal, gas, oil (fossil fuel), biomass
<1% conversion efficiency

direct conversion into electricity
in solar cells
lowest amount of entropy production
cleanest energy is electricity
conversion efficiencies 5…40 %

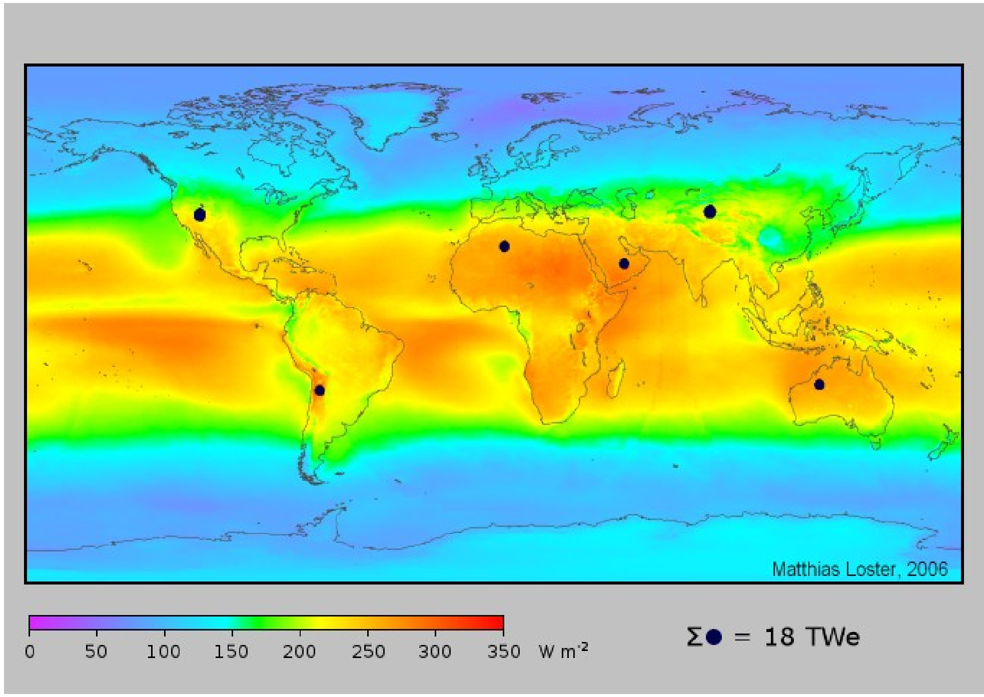
Bio mass for energy in Germany

photosynthesis
$C_6H_{12}O_6$, … converted into methanol, methan…

population density in Germany: 230 persons/km²
primary energy consumption: 6 kW/person

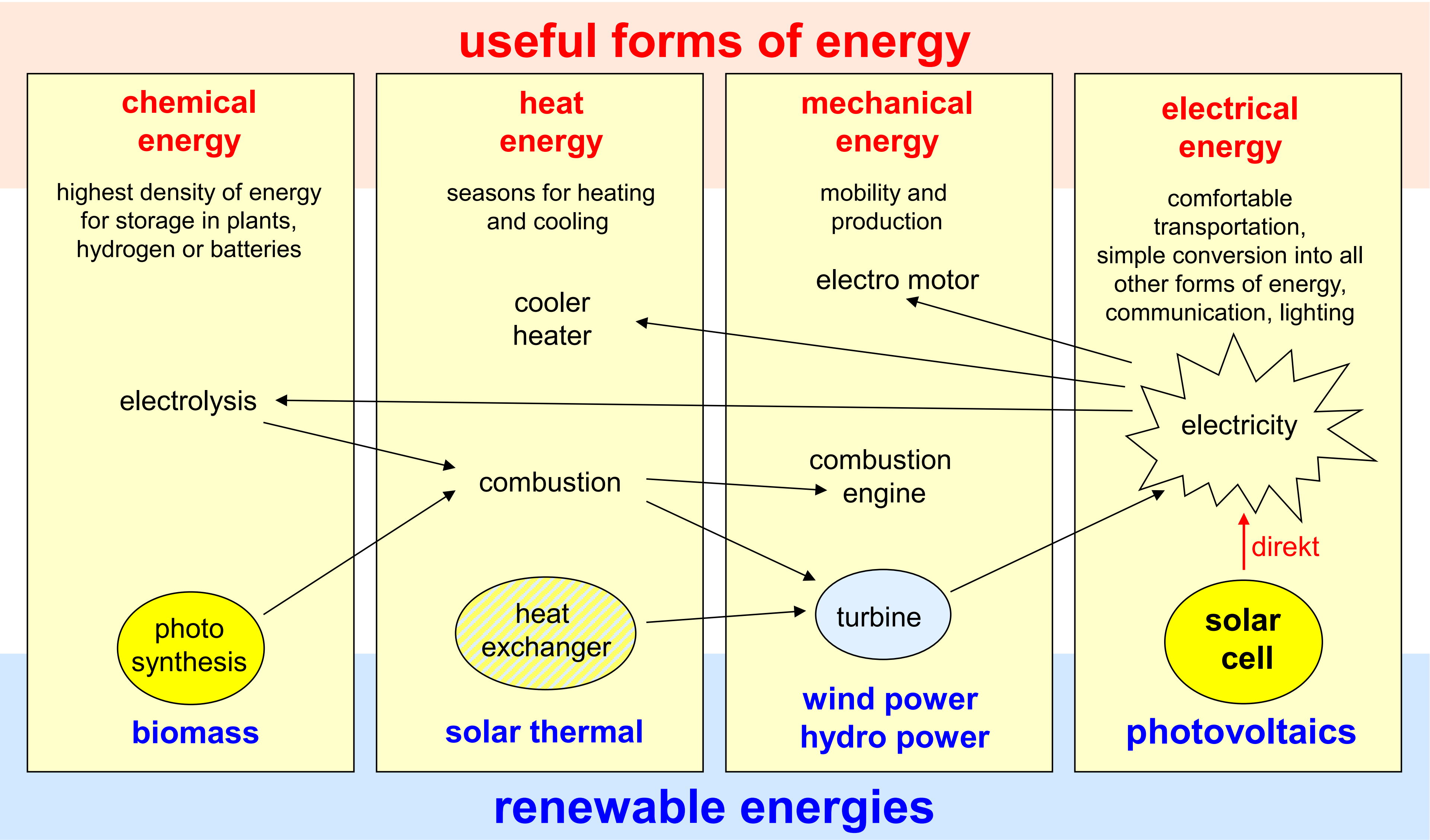
efficiency of photosynthesis about 1%
further losses in energy due to production of fuel from bio mass,…

demand for energy production: 1.4 MW/km²
average solar radiation in Germany: 150 MW/km²



→ Bio mass can supply only a minor part of energy needed in Germany

The future energy mix



useful forms of energy

chemical energy

highest density of energy for storage in plants, hydrogen or batteries

electrolysis

photo synthesis

biomass

heat energy

seasons for heating and cooling

cooler
heater

combustion

heat exchanger

solar thermal

mechanical energy

mobility and production

electro motor

combustion engine

turbine

wind power
hydro power

electrical energy

comfortable transportation, simple conversion into all other forms of energy, communication, lighting

electricity

direkt

solar cell

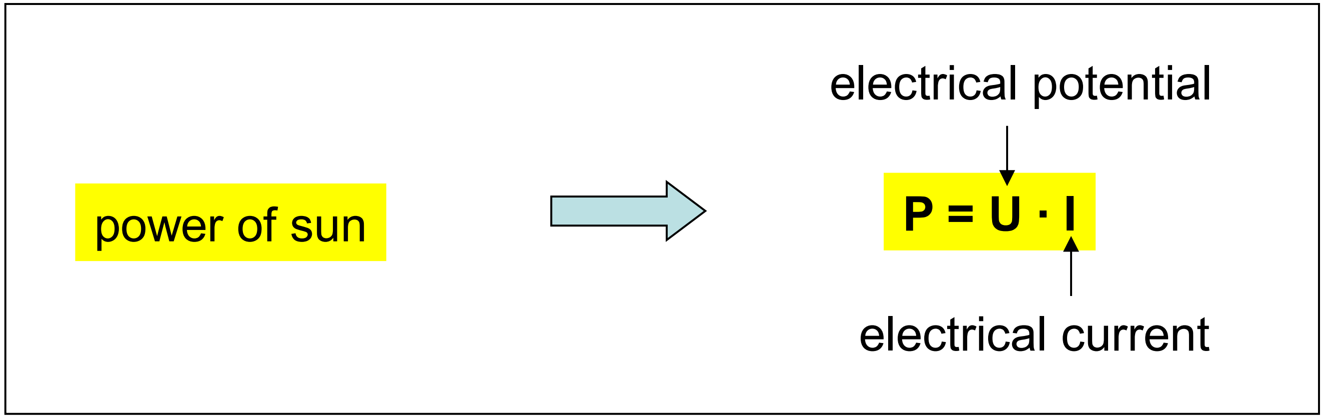
photovoltaics

renewable energies

Th. Dittrich, lecture notes

The solar cell

electronic device converting solar power directly into electrical power



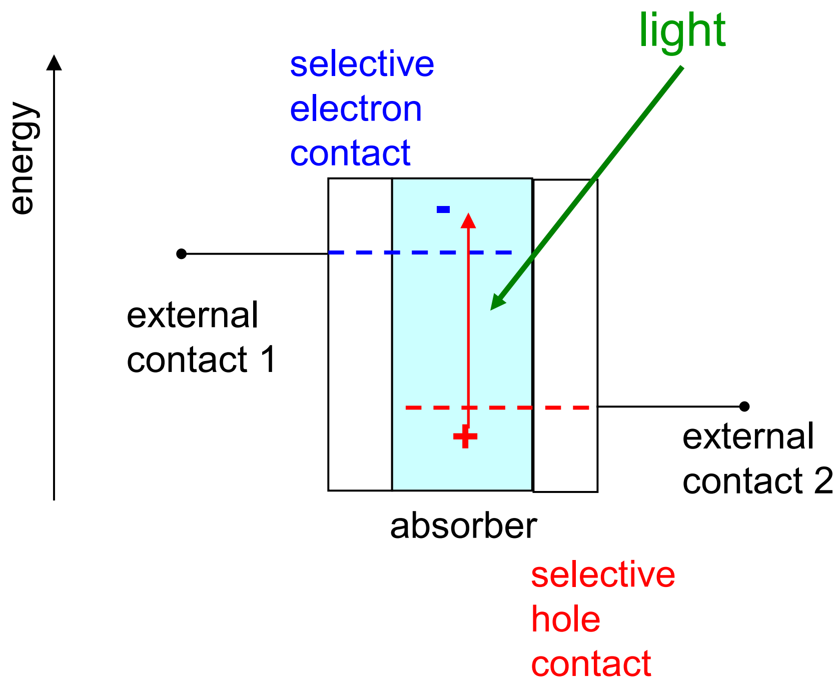
power of sun $\rightarrow$ $P = U \cdot I$

electrical potential

electrical current

A solar cell absorbs light and conducts electrons and holes to separate electron and hole collecting contacts.

A major characteristic is the **energy conversion efficiency η**.



energy

selective
electron
contact

light

-

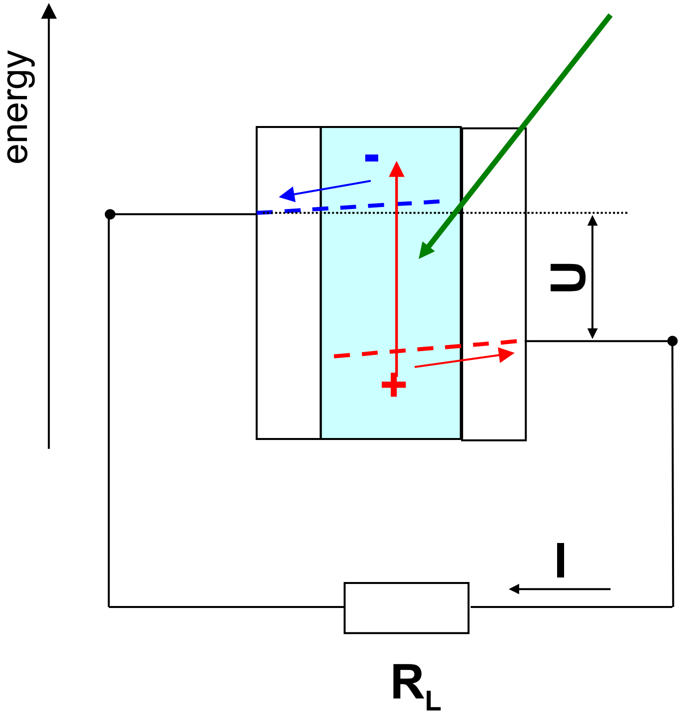
+

external
contact 1

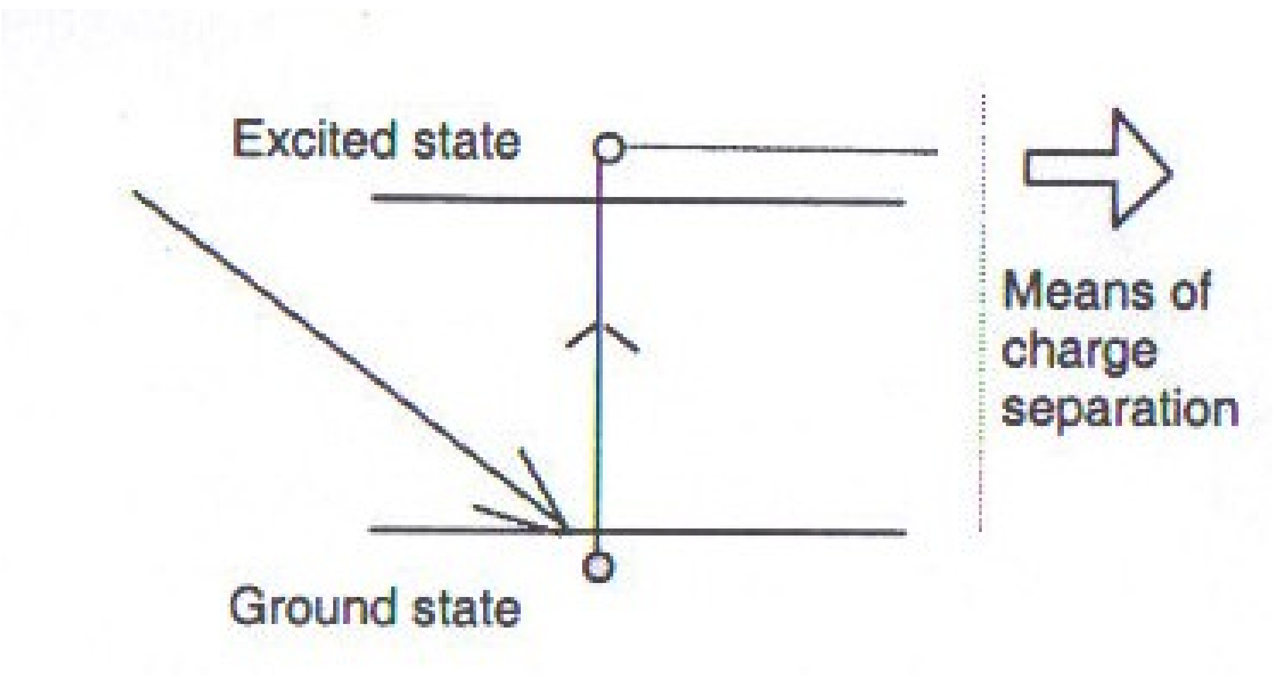
external
contact 2

absorber

selective
hole
contact


energy
-
+
U
I
R_L

Excitation and charge separation



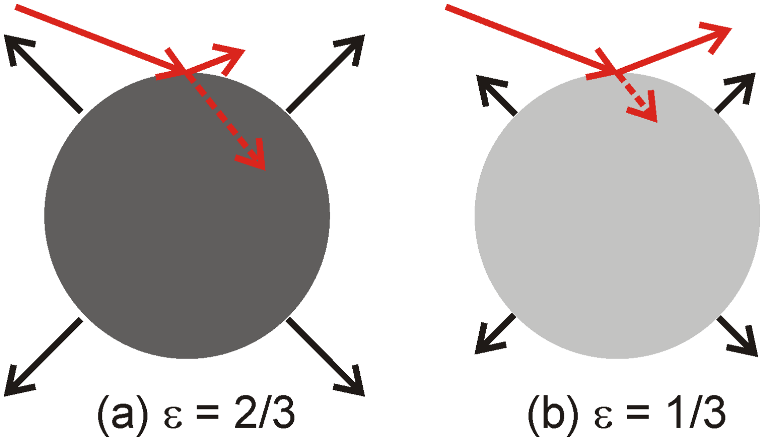
Photon creates electron-hole pair, which is separated by an asymmetric potential. Charge separation prevents relaxation to its initial state.

Energy balance

In order to reach an equilibrium situation, the photon flux absorbed by the solar cell must equal the emitted photons

⇒ Kirchhoffs law $\epsilon(h\nu) = a(h\nu)$

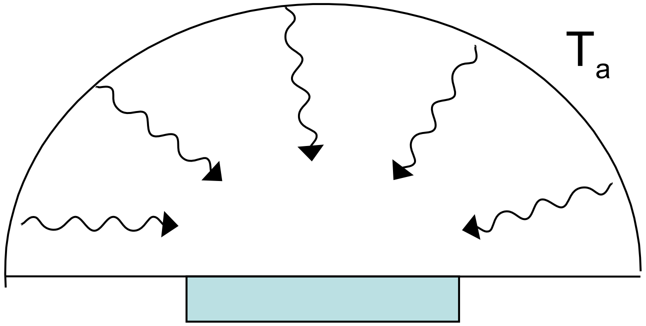
emissivity = absorbance (absorptivity)



http://de.wikipedia.org/wiki/Kirchhoffsches_Strahlungsgesetz

Cell in the dark: Absorption of thermal photons

$$b_a(E) = \frac{2F_a}{h^3c^2}(\frac{E^2}{\exp\frac{E}{k_bT_a} - 1})$$

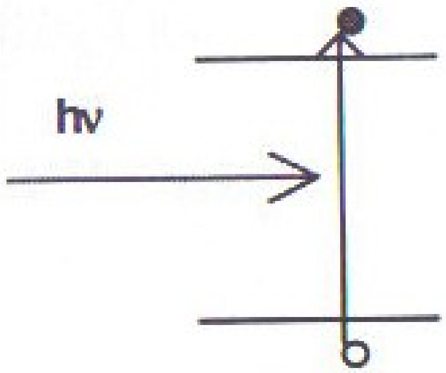


b_a : incident photon flux
h: Planck‘s constant
c: speed of light
k_B: Boltzmann constant
E: Energy
Thermal photons are absorbed from the environment of Temperature T_a
F_a: geometry factor; $F_a=\pi$ for hemisphere
a(E): absorbance

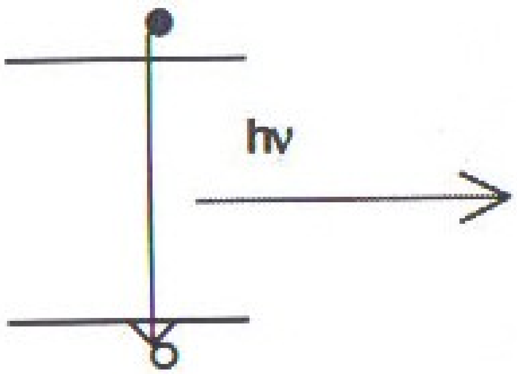
The equivalent current density j_{abs} absorbed from the ambient:

$$j_{abs}(E) = q(1 - R(E)) \cdot a(E) \cdot \frac{2F_a}{h^3c^2}(\frac{E^2}{\exp\frac{E}{k_bT_a} - 1})$$

Absorption and spontaneous emission



absorption



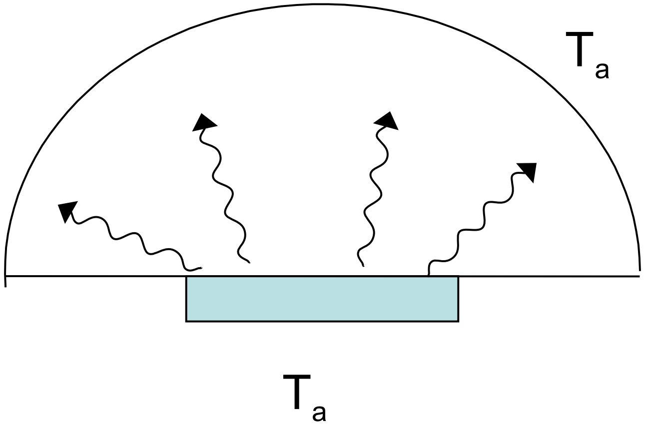
spontaneous emission

Cell in the dark: Emission of thermal photons

$$j_{rad}(E) = q(1 - R(E)) \cdot \epsilon(E) \cdot \frac{2F_a}{h^3c^2}(\frac{E^2}{\exp\frac{E}{k_bT_a} - 1})$$

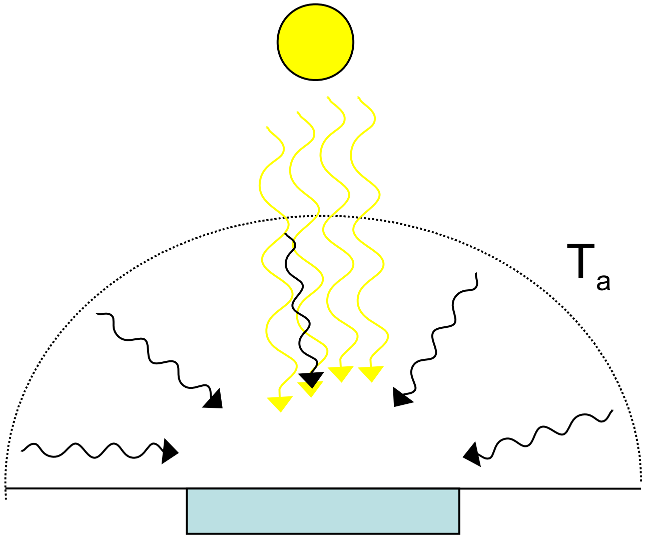
$$= q(1 - R(E)) \cdot \epsilon(E) \cdot b_a(E)$$

In equilibrium: Kirchoff's law $\epsilon(h\nu) = a(h\nu)$



Under illumination (absorption)

$$b_S(E) = \frac{2F_S}{h^3c^2}\left(\frac{E^2}{\exp\frac{E}{k_bT_S} - 1}\right)$$



T_s: Temperature of the sun

$F_s = \pi \sin^2\theta_s = \pi / 4.6 \cdot 10^4$

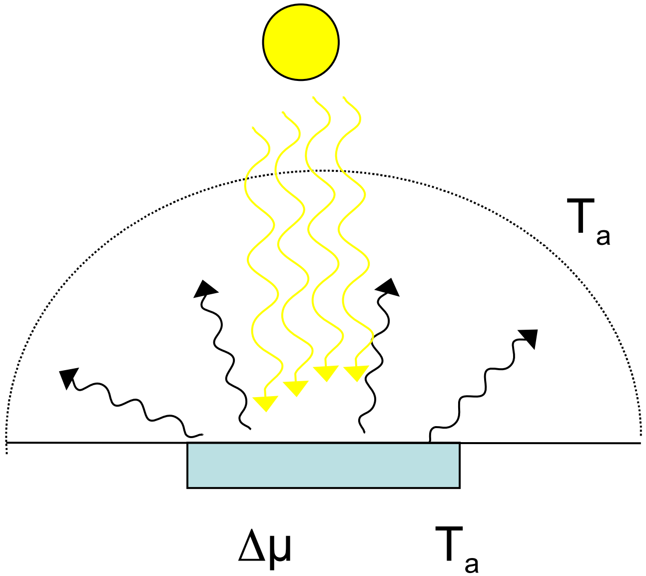
$\theta_s = 0.26°$

$$j_{abs}(E) = q(1 - R(E)) \cdot a(E) \cdot (b_S(E) + (1 - \frac{F_S}{F_e} \cdot b_a(E))$$

Under illumination (emission)

Depends on the Δμ (chemical potential). When electrons are at raised energy, relaxation is more frequent: Generalized Planck's radiation law:

$$b_e(E) = \frac{2F_a}{h^3c^2}\left(\frac{E^2}{\exp\frac{E-\Delta\mu}{k_bT_a} - 1}\right)$$



$$j_{rad}(E) = q(1 - R(E)) \cdot \epsilon(E) \cdot b_e(E, \Delta\mu)$$

Net current density under illumination

Under the assumption that $\epsilon(h\nu) = a(h\nu)$ and $\Delta\mu = const.$ across the cell

$$j_{abs}(E) - j_{rad}(E) = q(1 - R(E)) \cdot a(E) \cdot (b_S(E) + (1 - \frac{F_S}{F_e} \cdot b_a(E) - b_e(E, \Delta\mu)$$

Net absorption: $$j_{abs(net)}(E) = q(1 - R(E)) \cdot a(E) \cdot (b_S(E) - \frac{F_S}{F_e} \cdot b_a(E))$$

Net Emission
Radiative recombination $$j_{rad(net)}(E) = q(1 - R(E)) \cdot a(E) \cdot (b_e(E, \Delta\mu) - b_e(E, 0))$$

unavoidable loss!

Photocurrent

$$
\begin{aligned}
J_{SC} &= q\int_0^\infty \eta_c(E)\cdot(1-R(E))\cdot a(E)\cdot\left(b_S(E)-\frac{F_S}{F_e}\cdot b_a(E)\right)dE \\
&\approx q\int_0^\infty \eta_c(E)\cdot(1-R(E))\cdot a(E)\cdot b_S(E)dE
\end{aligned}
$$

η_C: probability that electron is collected

cf.

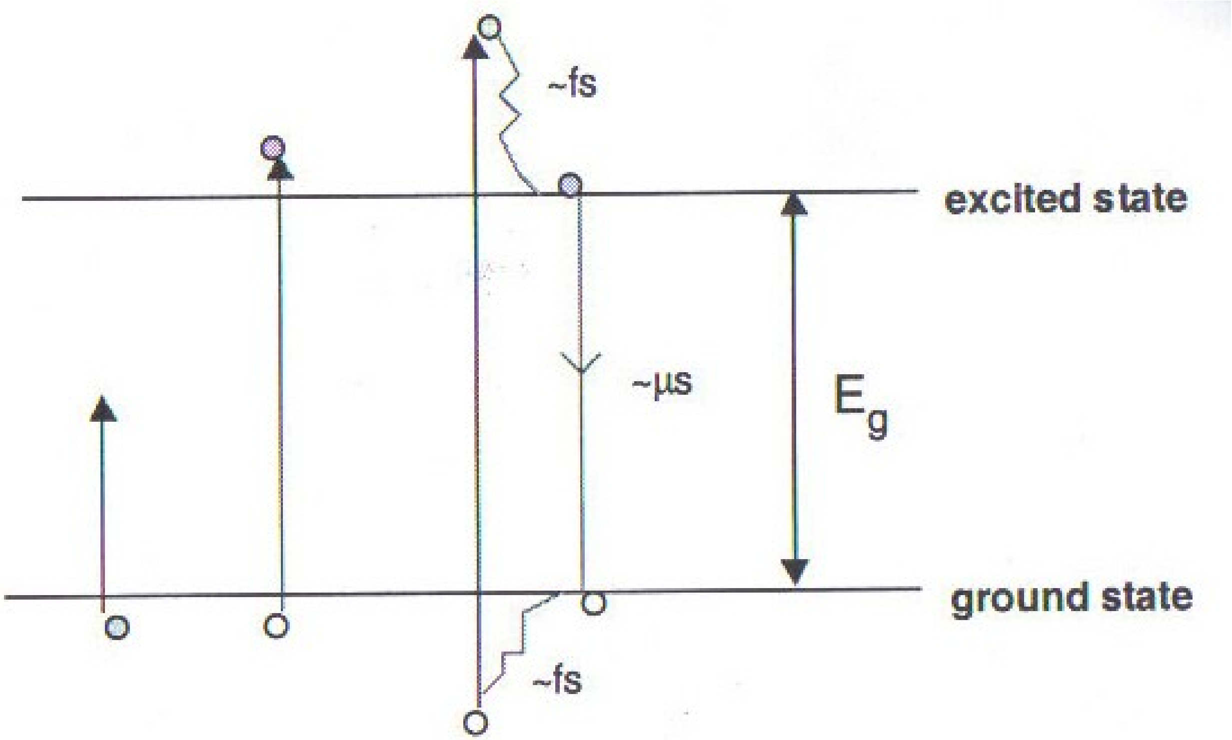
$$J = q\int_0^\infty QE(E)\cdot b_S(E)dE$$

Quantum efficiency: $QE(E) = \eta_c(E)(1-R(E))\cdot a(E)$

For non-reflecting material: R(E)=0 and perfect charge separation η_C=1:

$$QE(E)=a(E)=\begin{cases}1 & E\geq E_g\\ 0 & E< E_g\end{cases}$$

Two band photoconverter



Photons with $E>>E_g$ have the same effect like electrons with $E=E_g$

Photocurrent is rather proportional to photon flux and not photon energy

But photons with $E<E_g$ can not create electron hole pairs

Dark current

Assumption:

- only loss process is radiative relaxation of electrons through spontaneous emission
- No non-radiative losses due to scattering at defects in the material

$$J_{dark} = q\int_0^\infty (1 - R(E)) \cdot a(E) \cdot (b_e(E, \Delta\mu) - b_e(E, 0))dE$$

where $\Delta\mu = qV$

Dark current is related to emitted flux, which is increased with increasing voltage

Net cell current density

$$J(V) = J_{SC} - J_{dark} = q\int_0^\infty (1 - R(E)) \cdot a(E) \cdot (b_S(E) - (b_e(E, \Delta\mu) - b_e(E, 0)))dE$$

incoming flux

emitted flux

For step-like absorption ($E>E_g$):

$$J(V) = J_{SC} - J_{dark} = q\int_{E_g}^\infty b_S(E) - (b_e(E, \Delta\mu) - b_e(E, 0))dE$$

J(V) depends strongly on voltage:

$$J(V) = J_{SC} - J_0(\exp\frac{qV}{k_B T} - 1)$$

at $V=V_{oc}$ the total emitted flux balances the absorbed flux

Limiting efficiency

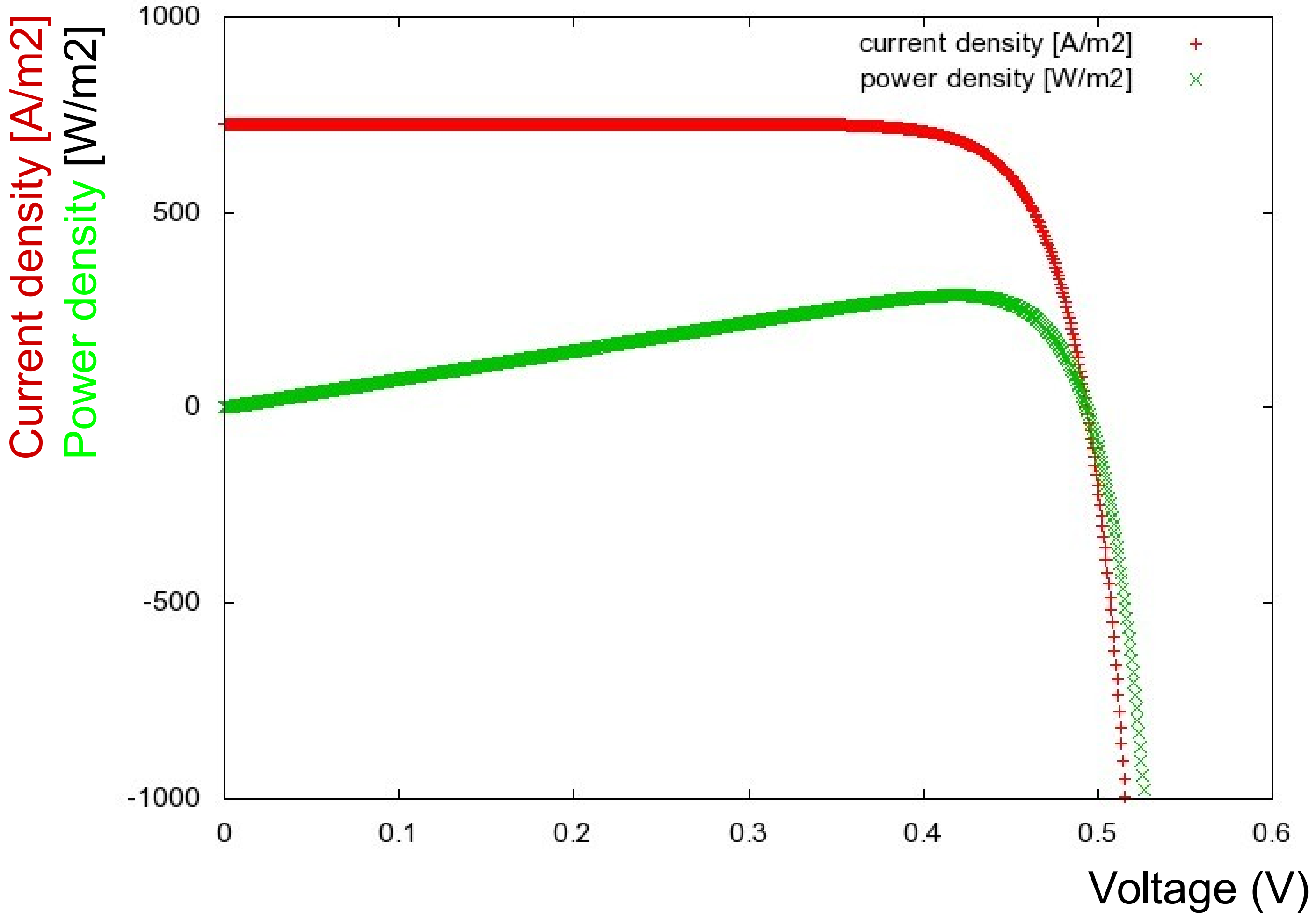
Incident power: $P_S = \int_0^\infty E_S(E)dE$

Output power density: $P = V \cdot J(V)$
(assumption no Ohm‘s losses)

Power conversion efficiency: $$\eta = \frac{V \cdot J(V)}{P_S}$$

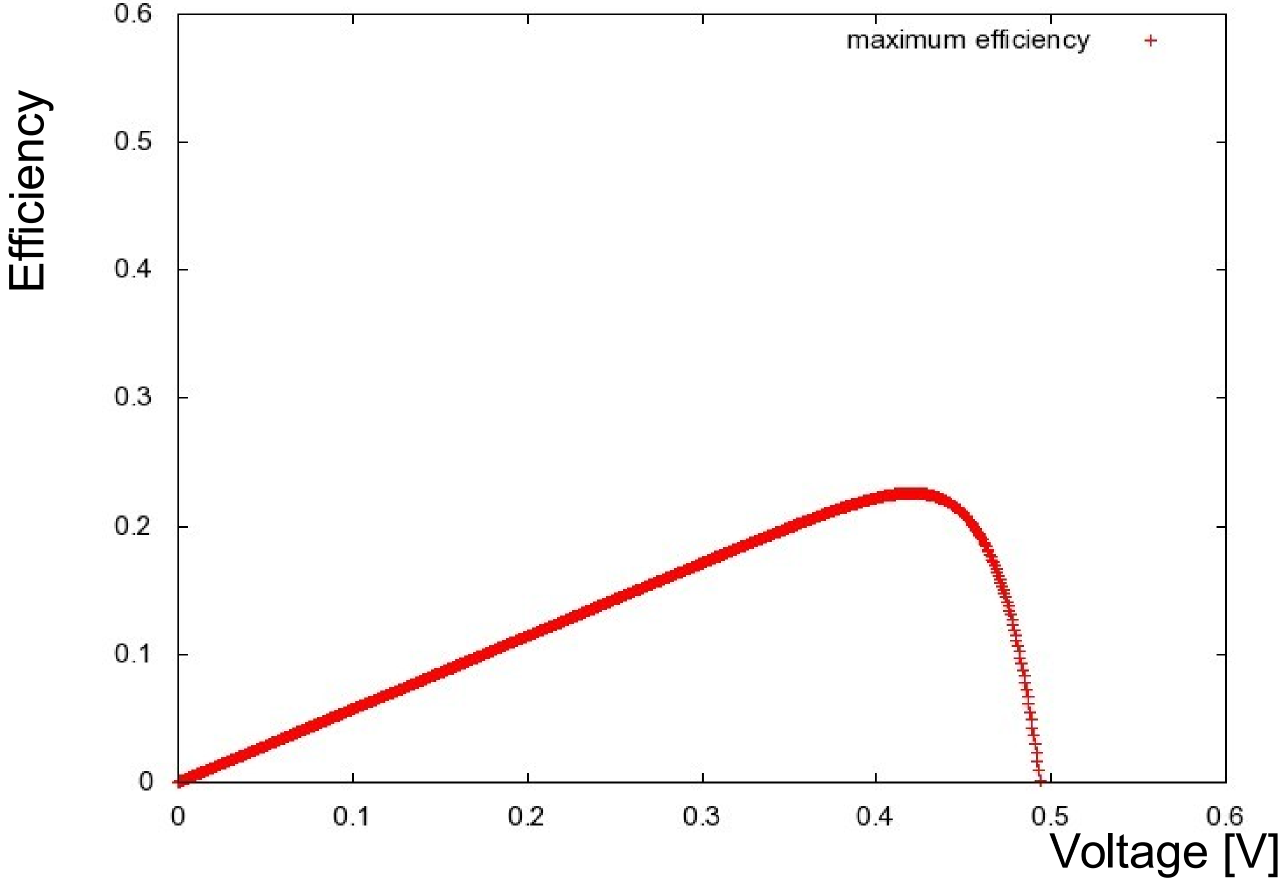
Maximum efficiency is achieved when: $\frac{d}{dV}(V \cdot J(V)) = 0$

Maximum current and power densities with E_g=0.7eV



E_g=0.7V T_s=5760K T_a=300K P_S=1375W/m^2

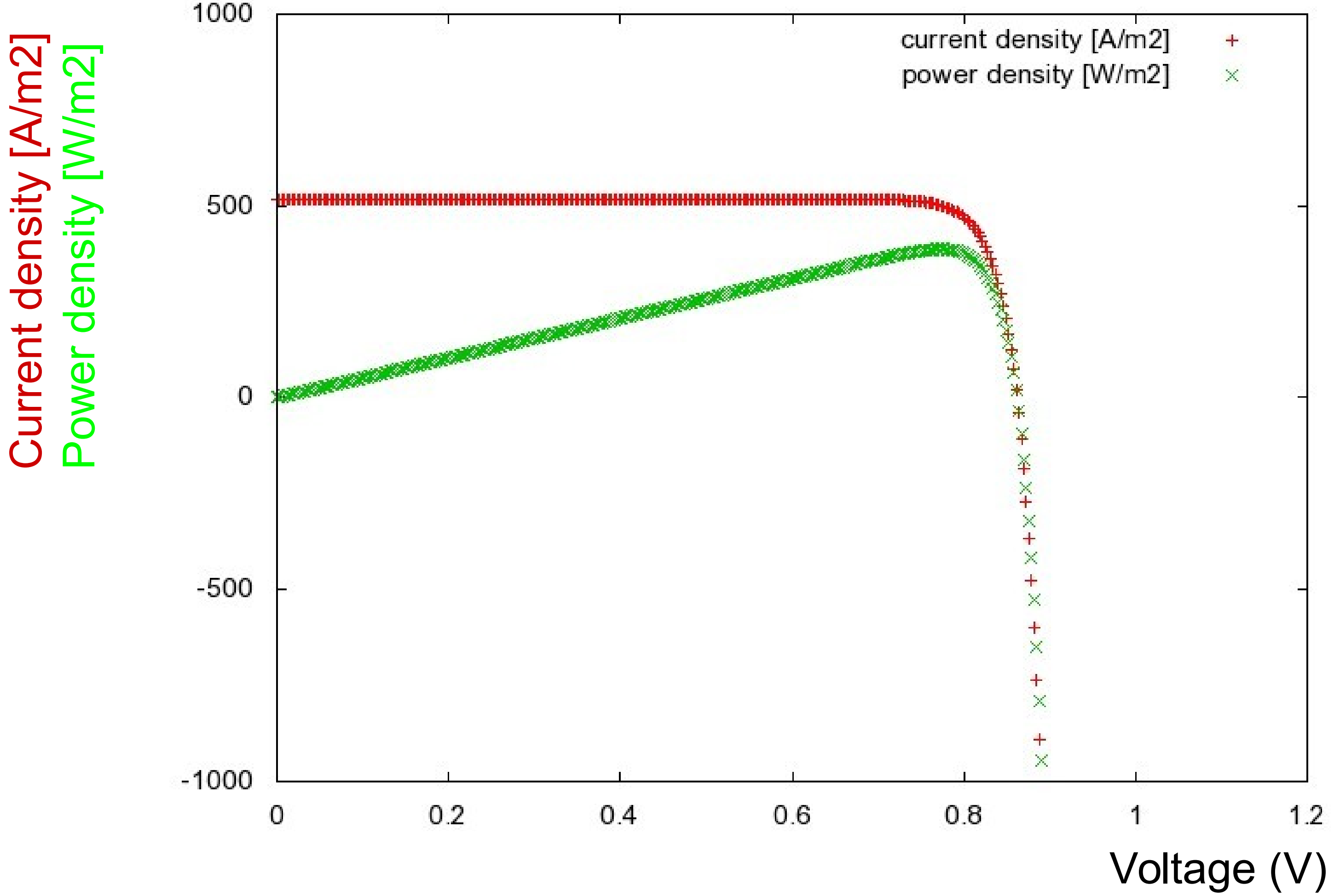
Maximum efficiency for E_g=0.7eV



$$\eta = \frac{V \cdot J(V)}{P_S}$$

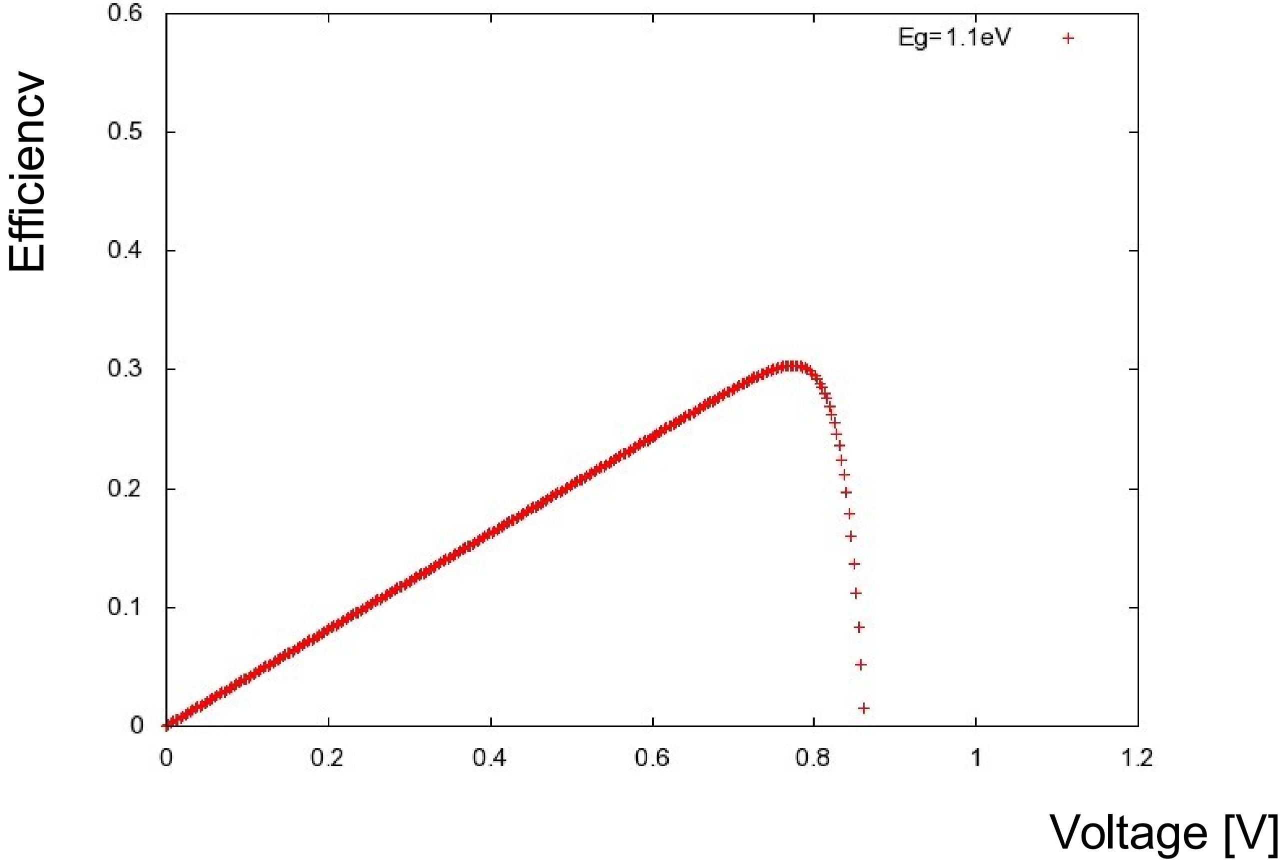
Best performance at V_m=0.45V with 22.5%

Maximum current and power densities with E_g=1.1eV



E_g=0.7V T_s=5760K T_a=300K P_S=1375W/m^2

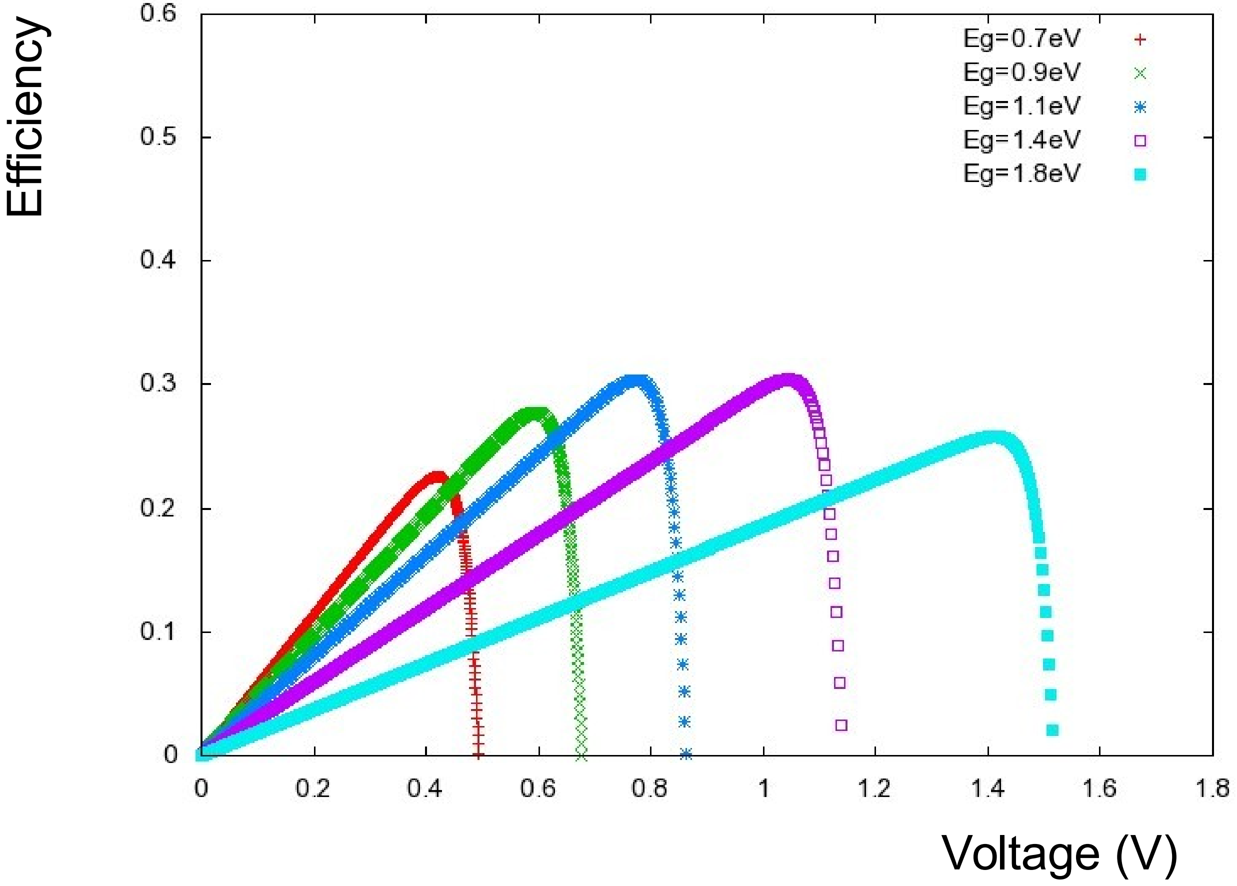
Maximum efficiency for E_g=1.1eV



$$\eta = \frac{V \cdot J(V)}{P_S}$$

Best performance at V_m=0.8V with 30%

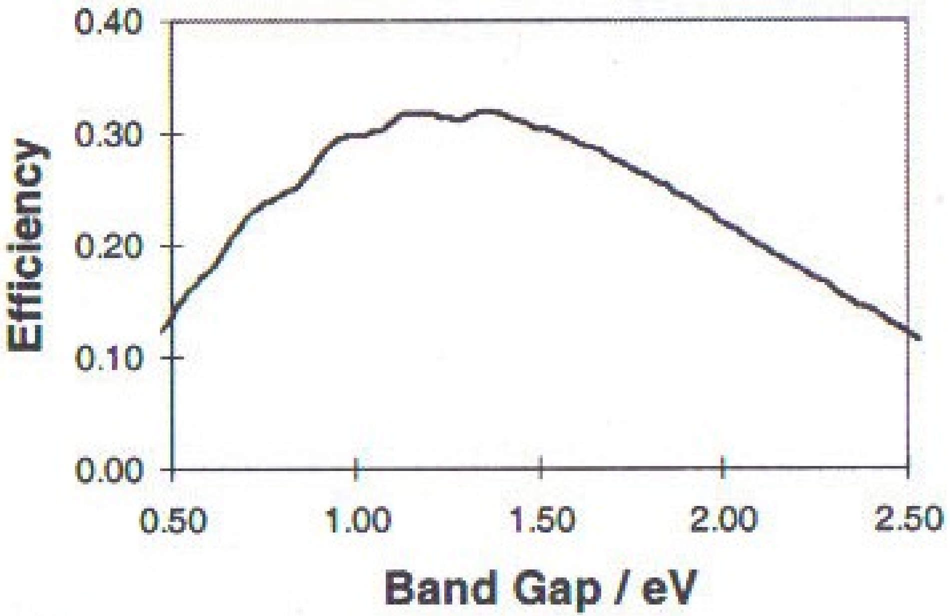
Maximum efficiency for different band gaps



$$\eta = \frac{V \cdot J(V)}{P_S}$$

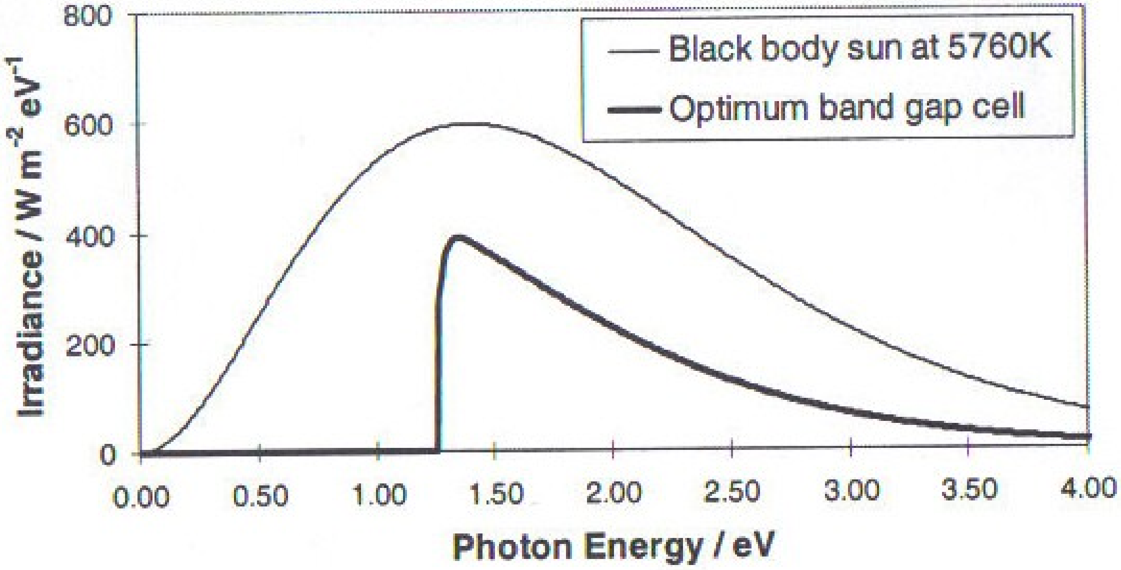
E_g=0.7-1.8V T_s=5760K T_a=300K P_S=1275W/m2

Limiting efficiency for a single band gap cell in AM 1.5



Optimum of a single band gap cell is 33% at 1.4eV

Power spectrum of a black body at 5760K and power available to a optimum band gap cell



Photons with E<Eg are not used
Photons with $E>>E_g$ have the same effect as $E=E_g$

Requirements for ideal photoconverter

- Energy gap E_g
- All incident radiation with $E>E_g$ is absorbed
- Each photon creates one electron-hole pair
- Excited pairs do not recombine, except radiatively, as required by the the balance
- Charges are completely separated
- Charges are transported without losses

Energy gap E_g

The optimum band gap for AM1.5 of 1.4eV with 33%

III-V-semiconductors: GaAs 1.42eV
InP 1.35eV
but expensive

Silicon 1.1eV would give a maximum efficiency of 29%
Cheap and high quality crystals available

CdTe and $CuInGaSe_2$ are developed

Other parameters

Light absorption: Almost perfect absorption with E>Eg is achieved
for layer thicknesses of 10-100 microns

Charge separation: Asymmetry is realized with pn-junctions
(either highly doped layers of same materials or different materials)
Junction quality is of central importance. (especially large areas)

Lossless transport:
Good Ohmic contacts, low resistance material for conduction (serial resistance),
No leakage current (parallel resistance)

Optimum load resistance:
Should be optimized to match best operating point
For most applications rather arrays than individual cells are to be optimized

Reasons for losses

- Reflection at front surface
- Non-radiative recombination of carriers
  (defect sites trap charges, which subsequently recombine)
- Voltage drop due to series resistance $\Delta\mu \neq qV$

Ways to improve

- Concentrators
- Tandem cells
- Organic cells with a variety of band gaps

Types of solar cells with regard to technology

Concentrator systems

Ge / $In_xGa_{1-x}As$ / $In_xGa_{1-x}P$
world record: **41.6%**
module efficiency: 28%
system efficiency: 23%

direct sun light is demanded

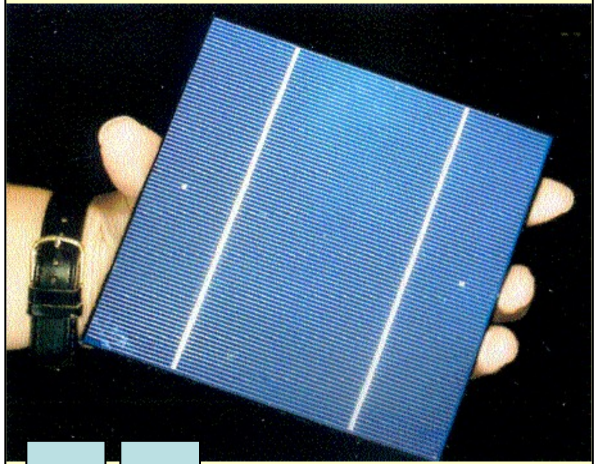
need for optical tracking

Si-wafer-based

c-Si, mk-Si
world record : 24.7%
module efficiency : 18%

energy intensive production of Si (very high purity needed)

dominant on market



Thin film

a-Si:H, nc-Si, CdTe, $Cu(In,Ga)(S,Se)_2$
nanostructured solar cells
organic solar cells
world record :
19.9% $Cu(In,Ga)Se_2$

integrated series connection

largest cost reduction potentials