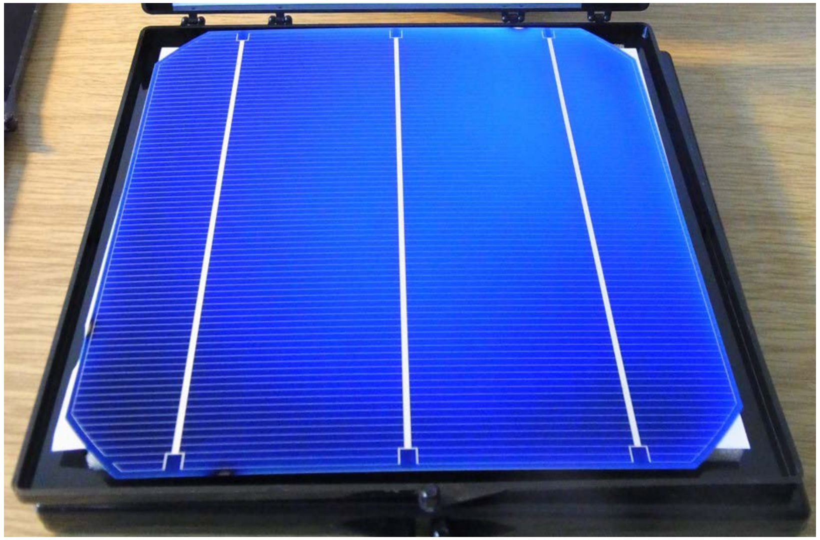
Konfektionierung einer 50mm x 50mm Solarzelle aus einer größeren Zelle

PV-Praktikum

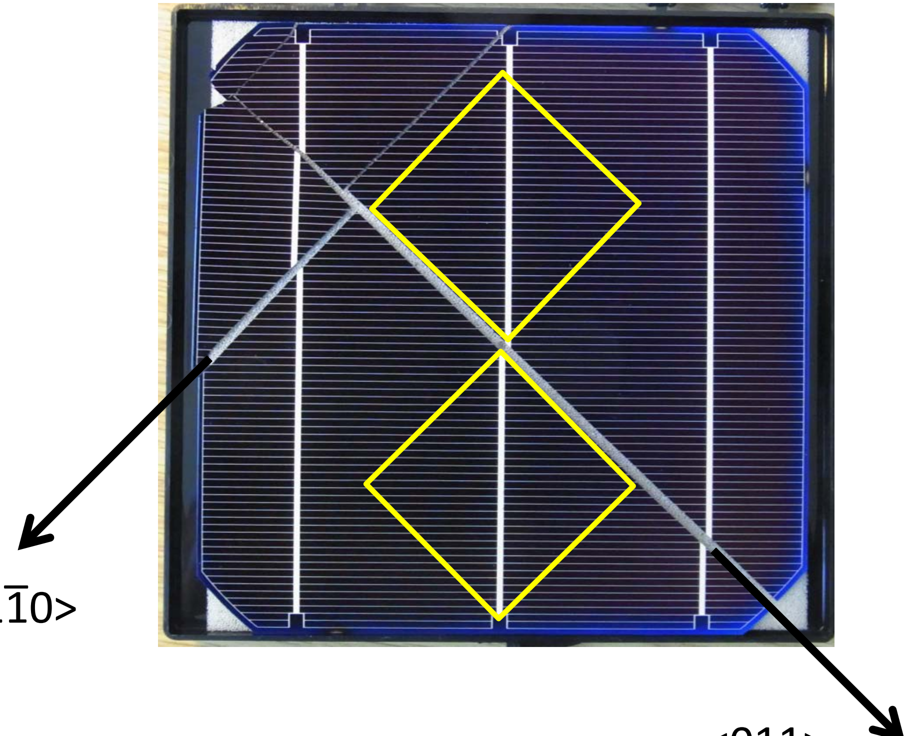
Ritzen/Brechen - Kleben - Löten - Kontaktmontage

Technische Universität Dresden
Institut für Angewandte Physik
Lehrstuhl für Halbleiterphysik

Cut-out of 50 mm x 50 mm test structures



Complete Cz-Si solar cell



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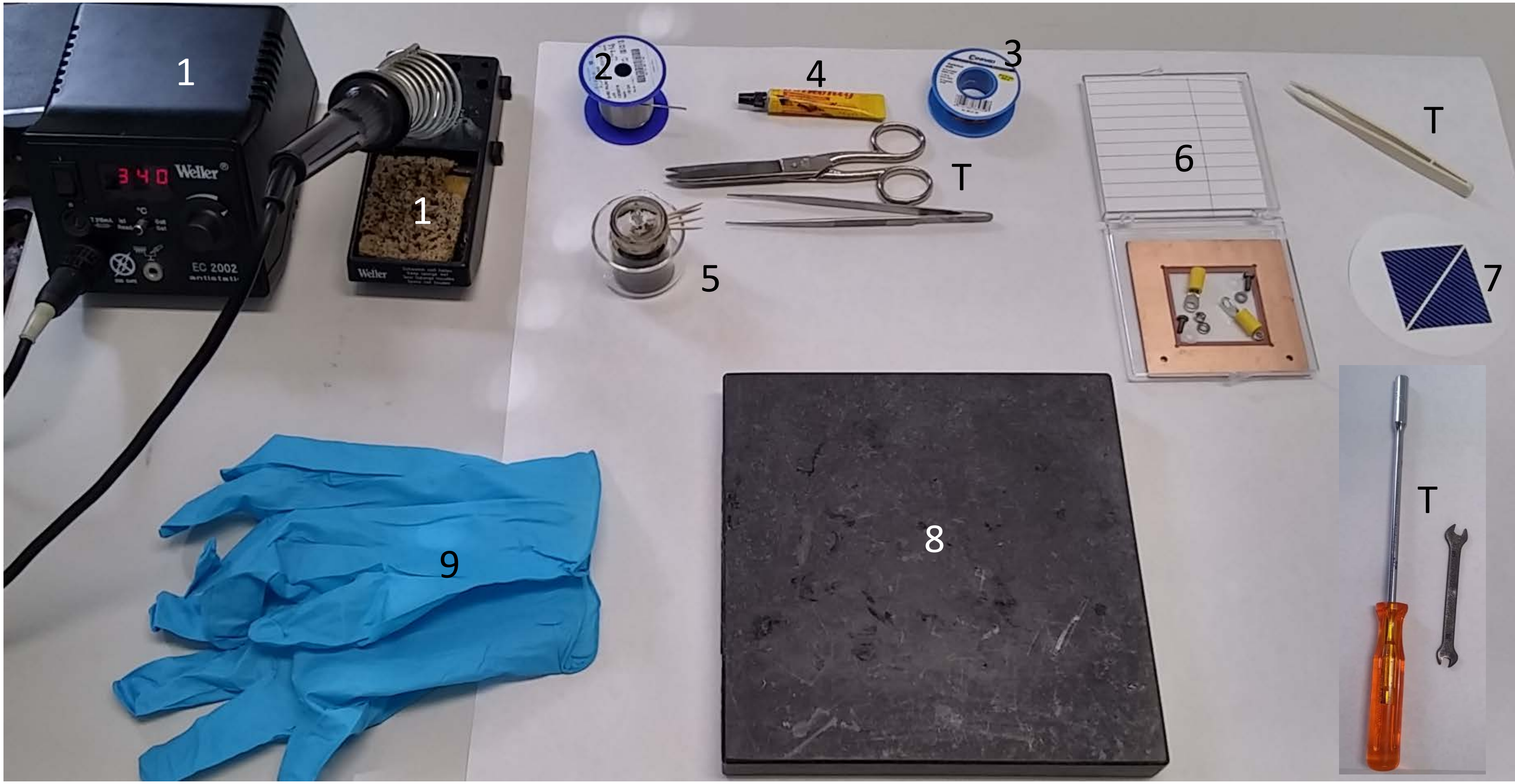
50 mm x 50 mm test structure

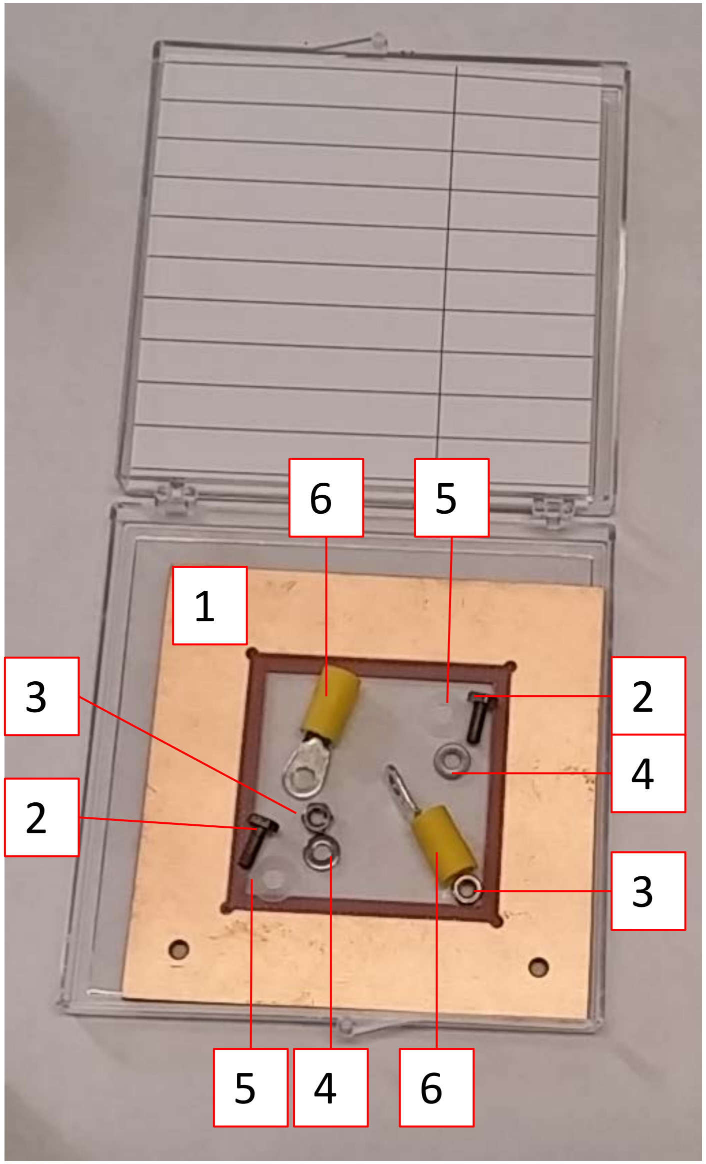
A set of necessary materials and instruments



1. Soldering Iron (30 Watt);
2. Solder wire $Sn_{60}/Pb_{38}/Cu_{2}$ (Flutin 1532);
3. Cu wire (∅ 0.15 mm);
4. Lothonig Super Flux (775-95);
5. Varnish (Asphaltlack);
6. Assembly kit (see next page);
7. Test Structure;
7. Stone plate;
8. Gloves;

T. Tools.

Assembly kit



1. Frame (Pertinax plate with Cu cladding on both sides);
2. Stainless steel screws M3 (×2);
3. Stainless steel nuts M3 (×2);
4. Stainless steel spacers (×2);
5. Plastic spacers (×2);
6. Contacting connectors (×2).

Preparation of wires

! Use the gloves during the whole process of assembling !

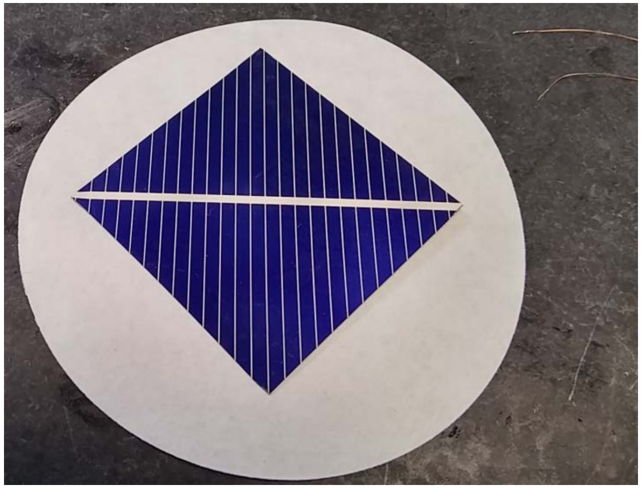
Set temperature of the soldering iron to 340°C

Cut 2x ~30 mm wires

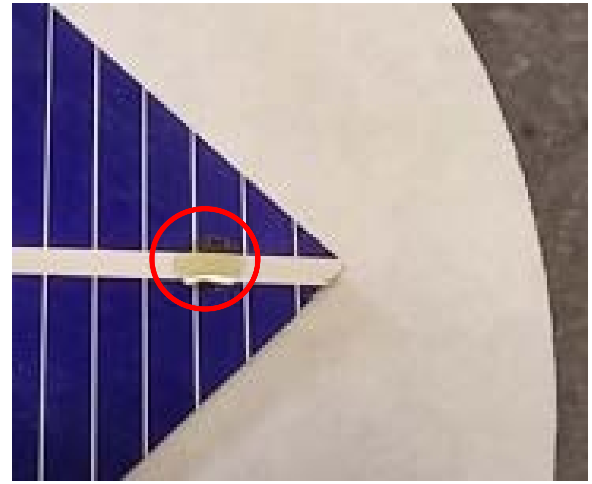
Solder both ends for each wire (2-3 mm long).

2-3 mm long

Attach front contact to the test structure

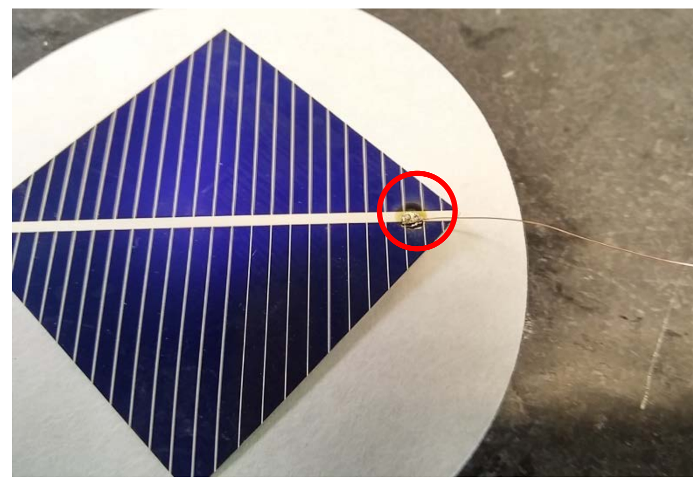


Place test structure on the stone plate.



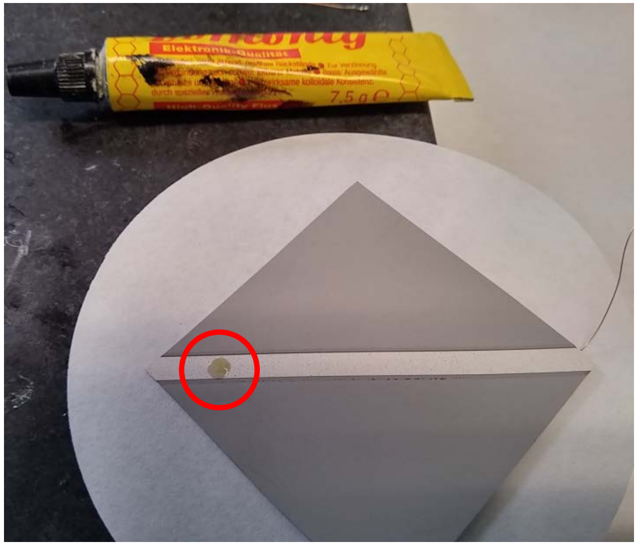
Put a tiny drop of flux on the busbar.

Attach soldering solution using the iron.

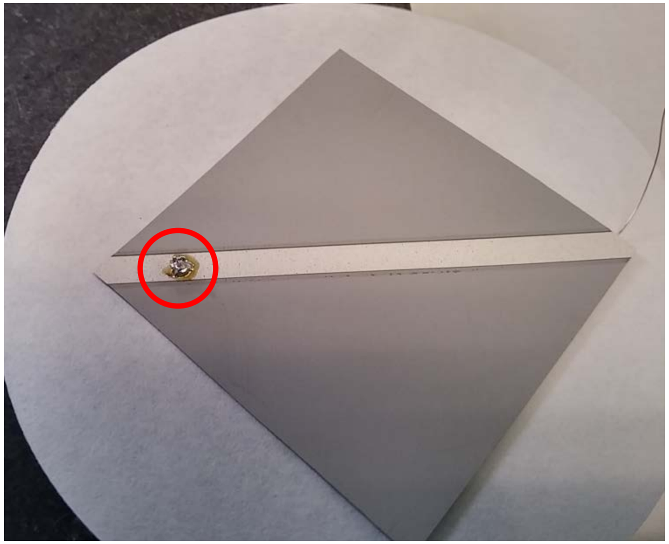


Attach wire using the soldering iron.

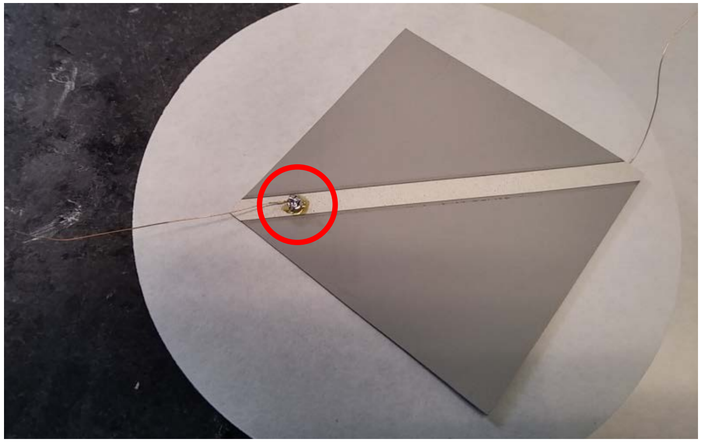
Attach back contact to the test structure



Put a tiny drop of flux on the busbar.
! Keep the soldered front contact outside the stone plate !

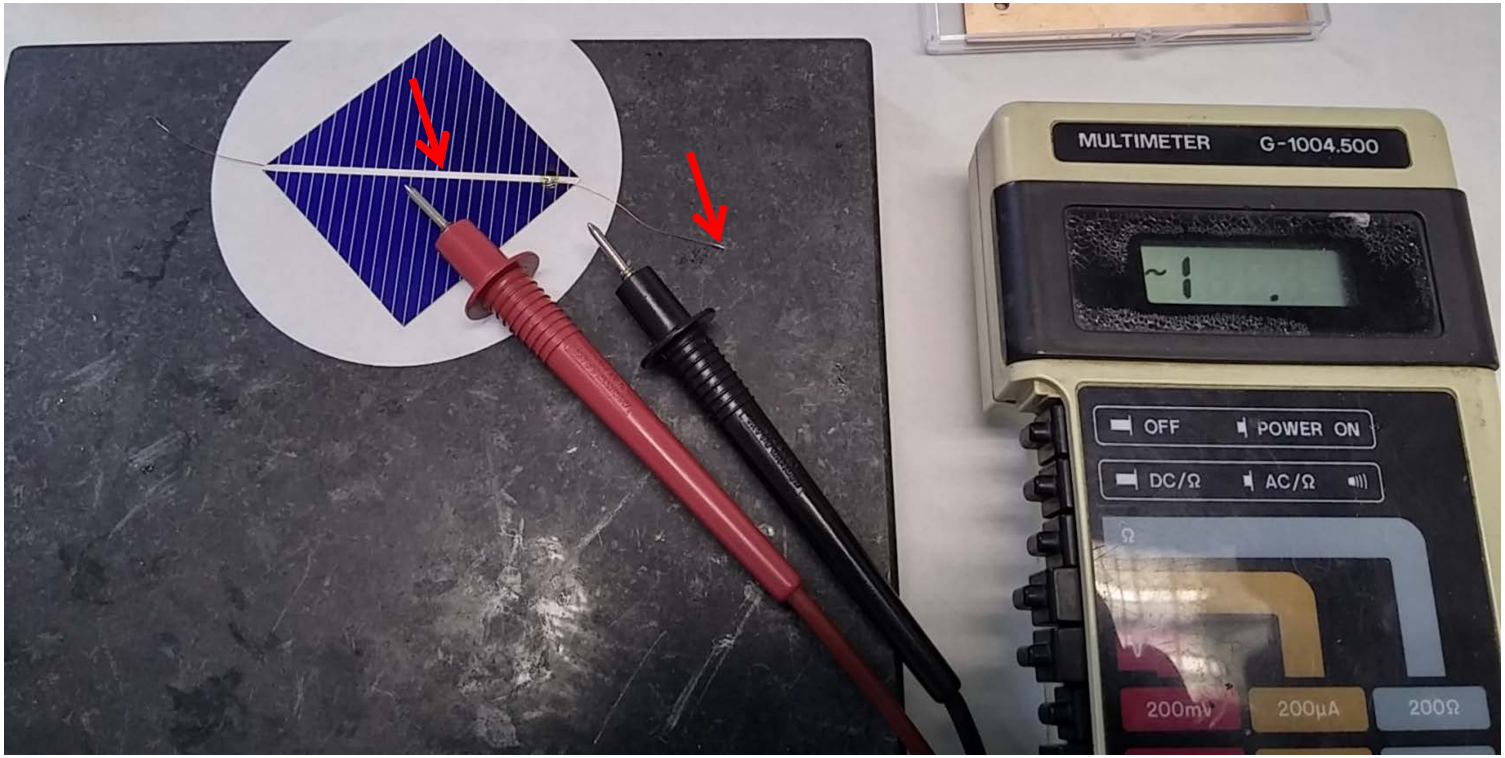


Attach soldering solution using the iron.



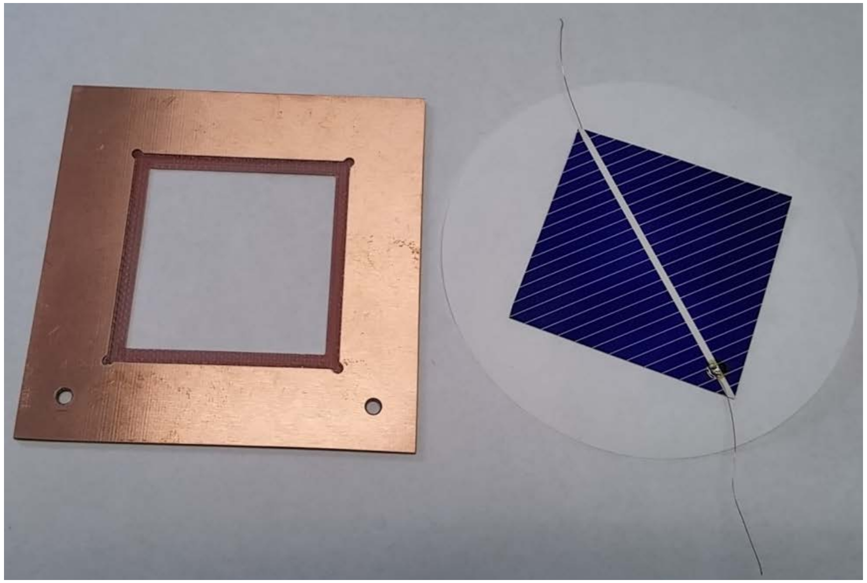
Attach the wire using the soldering iron.

Check of the contacts using multimeter

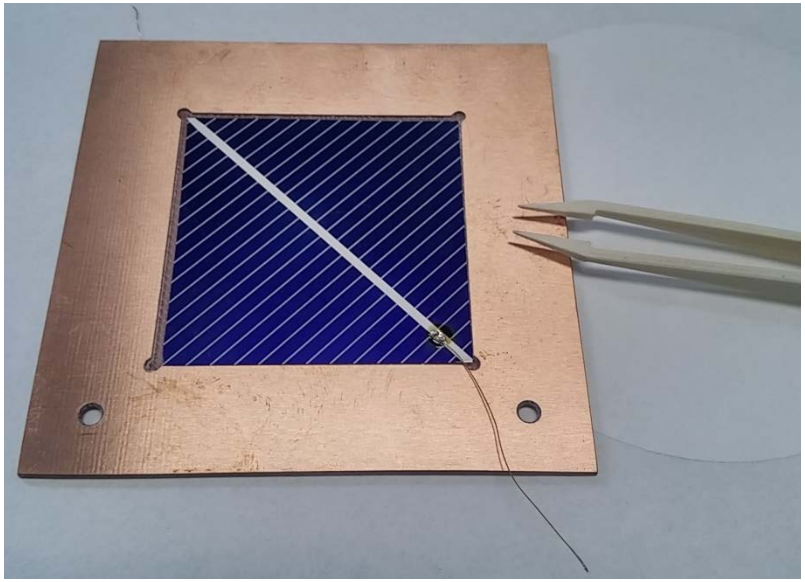


- Set multimeter to the “Short” checking mode;
- Check the contact quality for the front and for the back contacts by touching the busline and the end of the contacted wire.

Framing the test structure

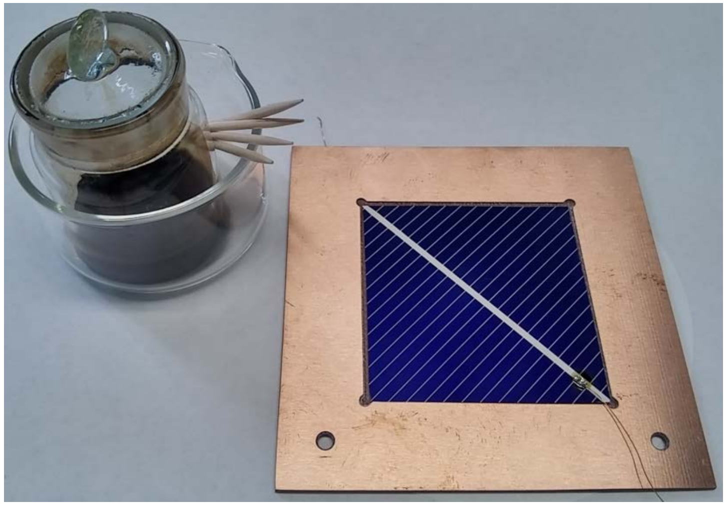


Take the frame from the assembly kit.

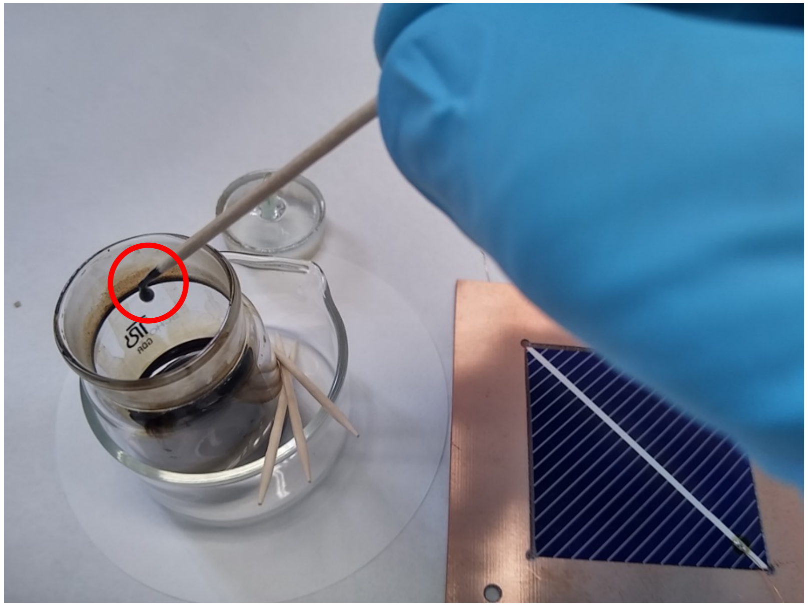


Carefully place the test structure inside the frame using the plastic tweezers.
! Keep the soldered wires out of the frame!

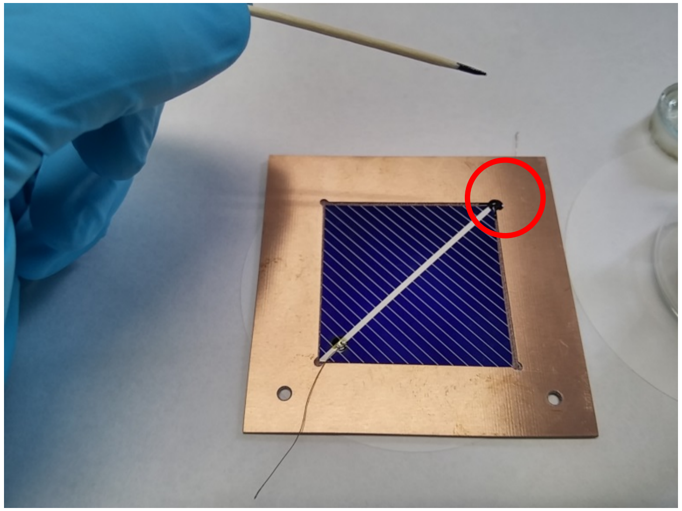
Framing the test structure



Bring the varnish close to the sample.

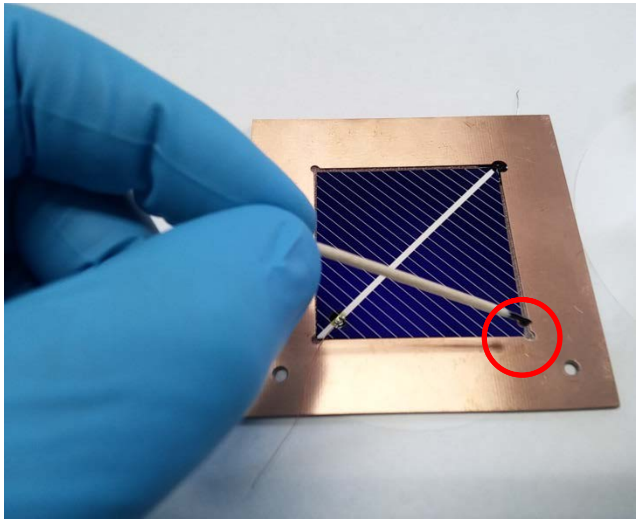


Take a small drop of the varnish using a toothpick.

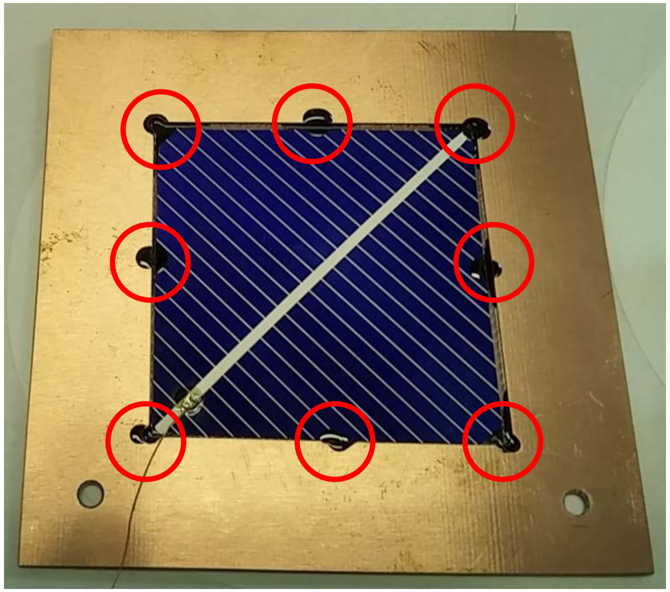


Place the drop in the corner of the frame on the top of the test structure and the frame.

Framing the test structure



Repeat same with the second corner.

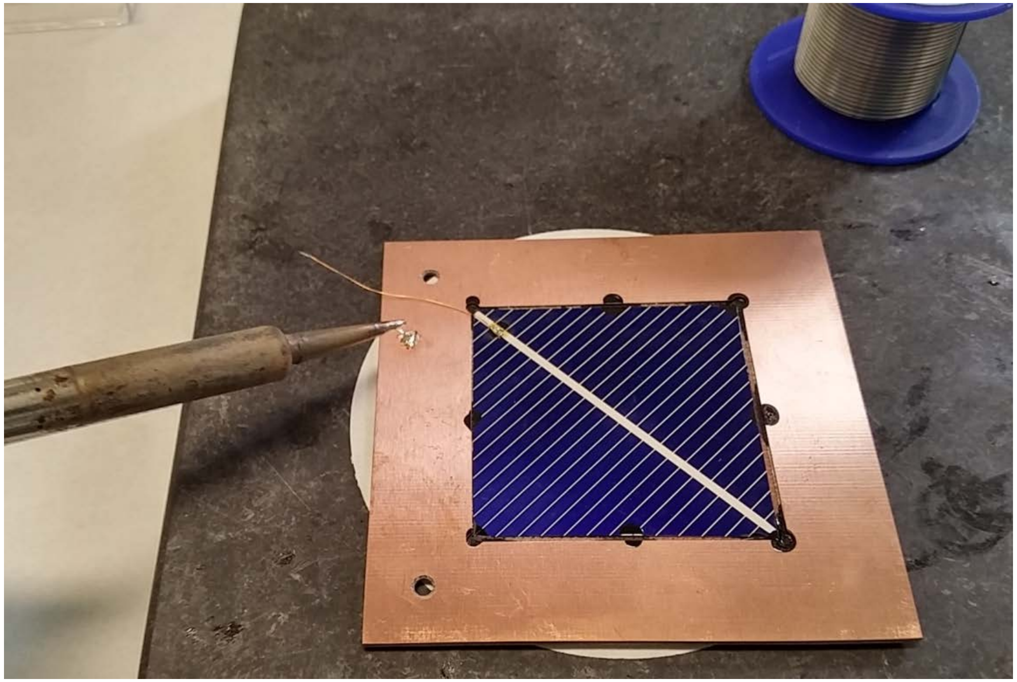


Repeat the same for the rest of the corners and for mid positions.

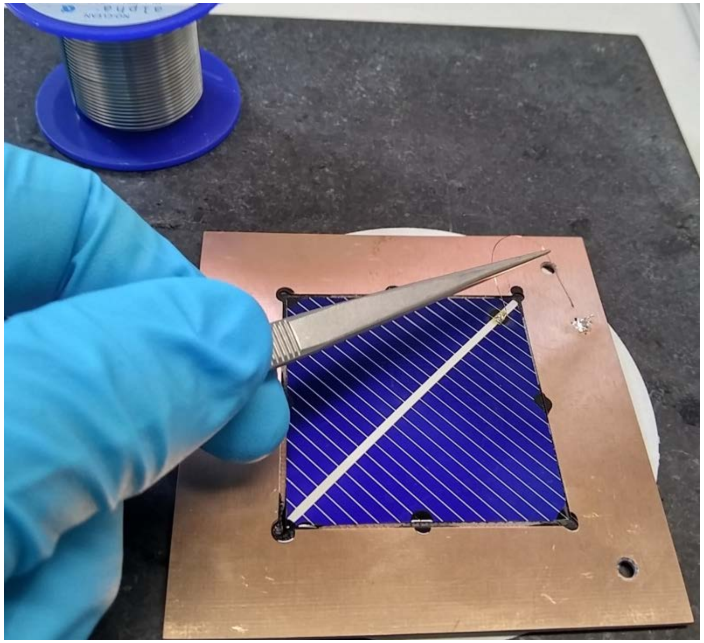
Wait 15-20 min for the varnish to dry.

! Check if the test structure is well attached to the frame by flipping the frame !

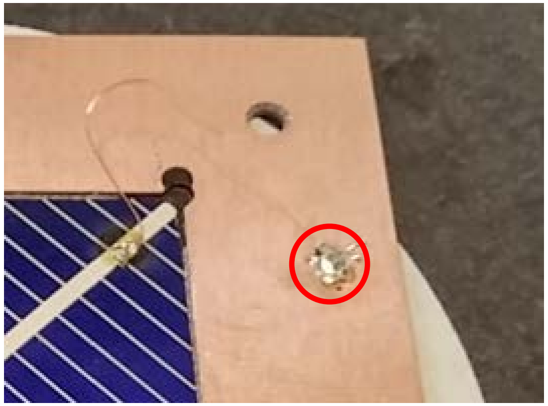
Connecting the wires to the frame



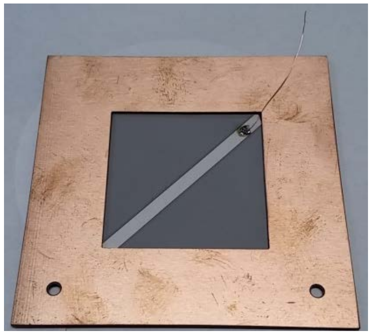
Make a pad on the frame using the soldering iron.



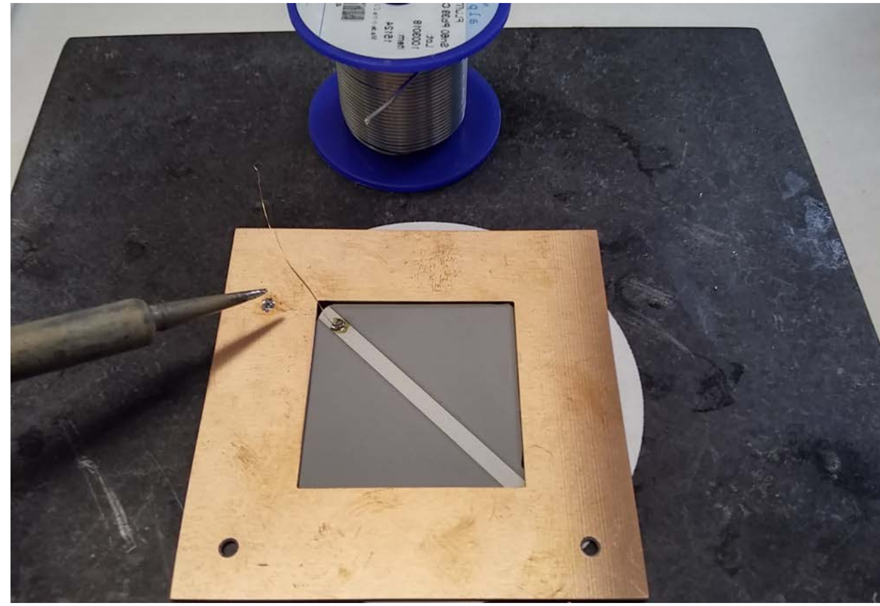
While holding the wire with the tweezers, attach it to the pad using the soldering iron.



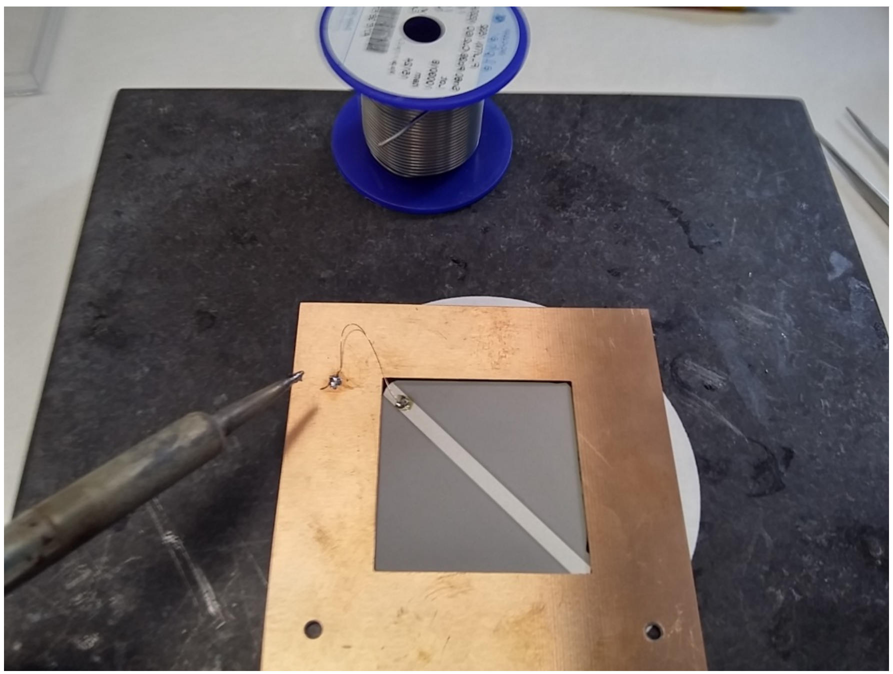
Connecting the wires to the frame



Flip the frame.

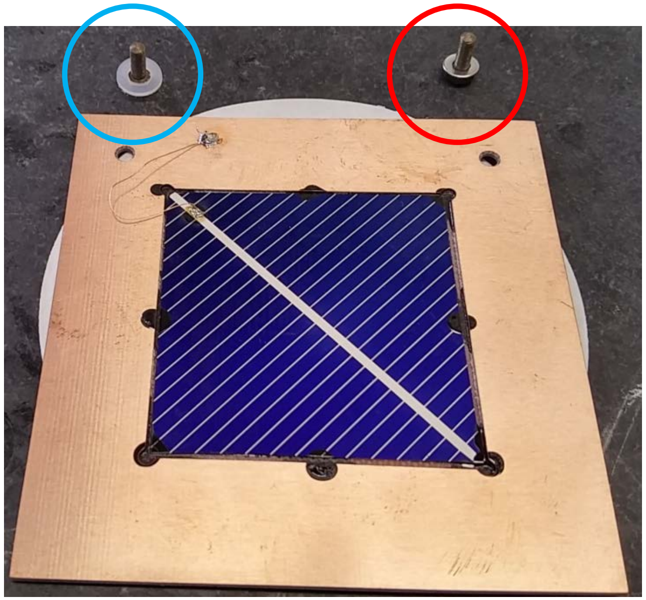


Make a pad on the frame using the soldering iron.

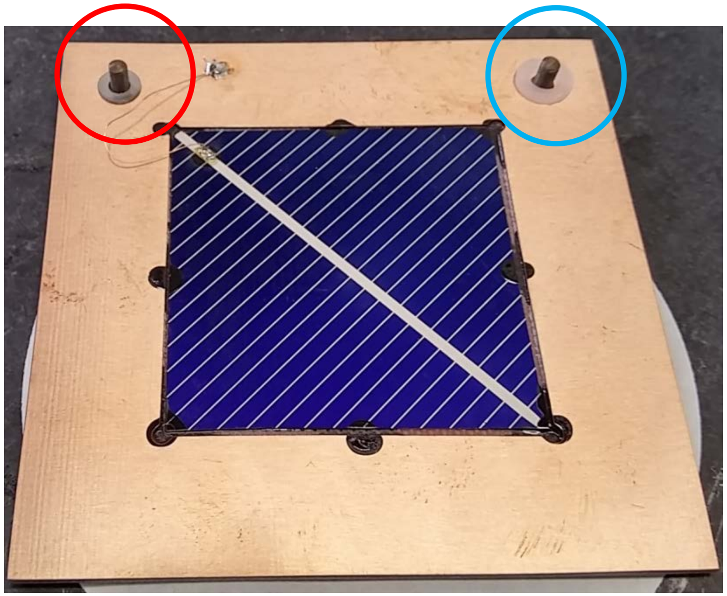


Attach the wire to the pad.

Assembling the contacts

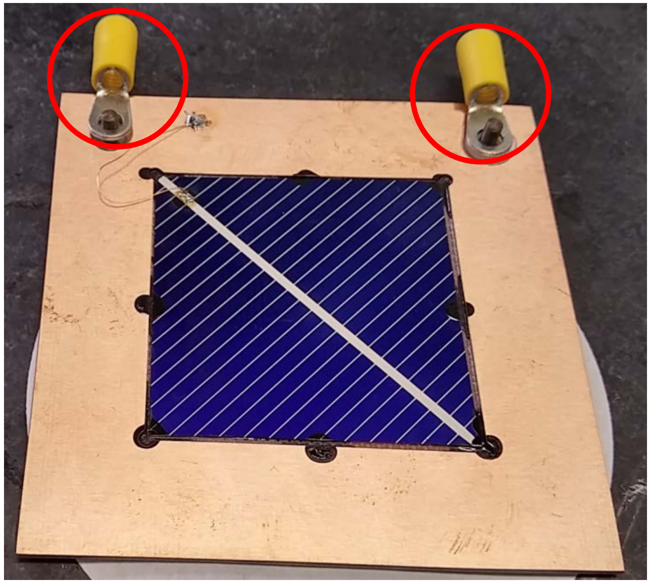


Face the structure up and prepare the screws with one plastic and another metallic spacers.

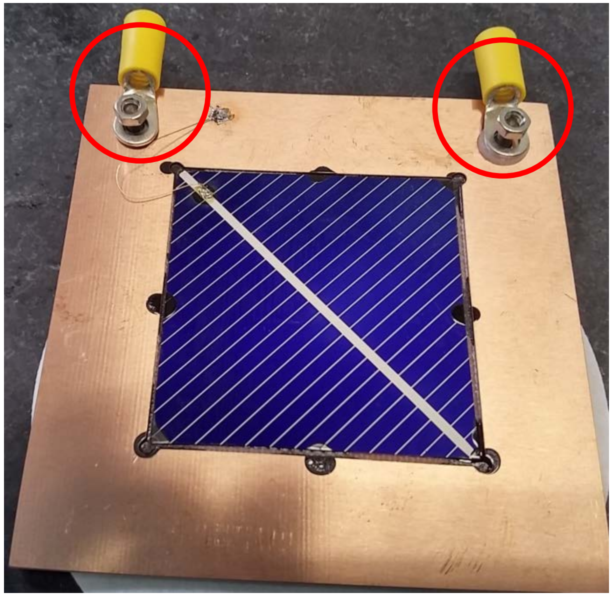


Pass the screws through the holes in the frame and put the rest spacers in opposite order: the metallic one for the screw with the first plastic spacer and the plastic for the first metallic spacer.

Assembling the contacts



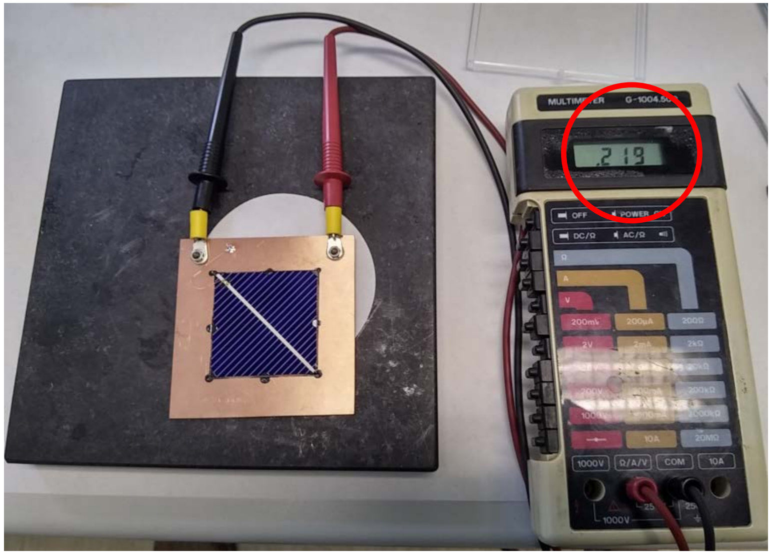
Pass the screws through the contacting connectors.

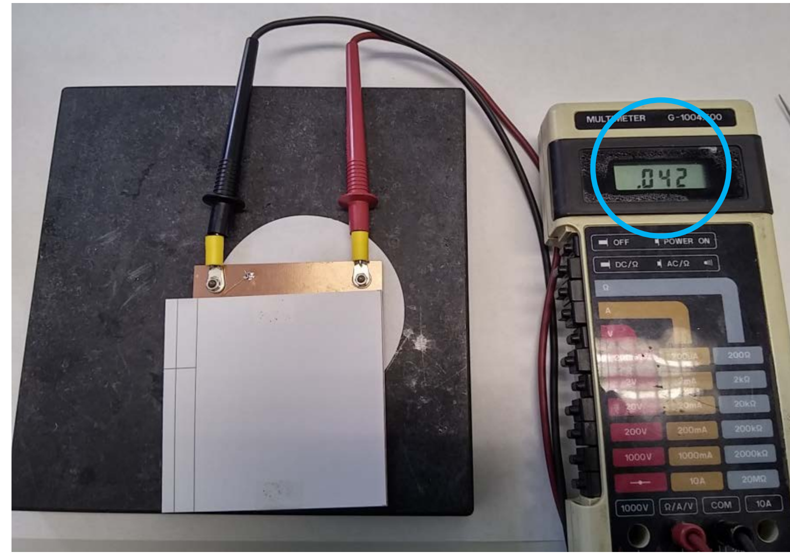


Attach the screw-nuts.

Tighten the connections using the tools.

Check your test structure





Check your test structure by measuring the open circuit voltage (V_{OC}) between the contacts. If the assembly was correct, the V_{OC} will be larger under illumination and it will be smaller if the cell is covered with sheet.

Place the structure inside the pocket from the kit and save it for the further test measurements.

ფოტოვოლტაიკა

თეიმურაზ მჭედლიძე
დრეზდენის ტექნიკური უნივერსიტეტი
თებერვალი 2016

ლექციების გეგმა

1. შესავალი;

   მზე როგორც ენერგიის წყარო.

2. მზის ენერგიის გარდაქმნა ელექტრობად

   ნახევარგამტარების საშუალებით.

3. ფოტოვოლტაიკური ელემენტები, მოდულები,

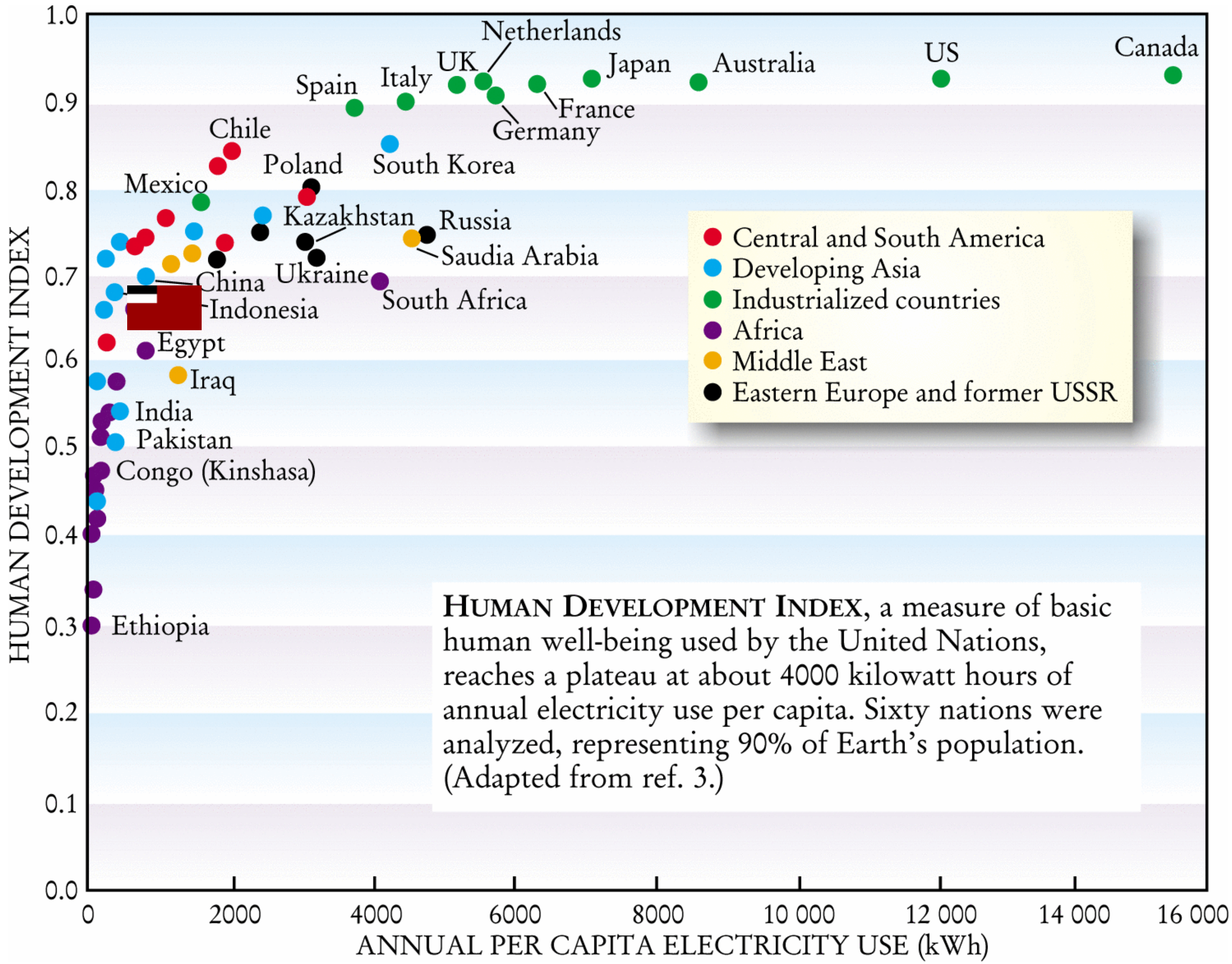
   ქსელები;

4. დასკვნები და მომავლის პერსპექტივა.

ლექცია I: მზე როგორც ენერგიის წყარო

- შესავალი
- მზის გამოსხივების სიმძლავრე და სპექტრი;
- დედამიწამდე მოღწეული მზის გამოსხივების სიმძლავრე;
- სეზონური და დღე-ღამური ცვლილებები;
- პირდაპირი და დიფუზიური გამოსხივება;
- ინსოლიაცია და ინსოლიაციის რუქები;
- მარტივი შეფასებები.

Human development index (HDI)



S.G. Benka, Physics Today 55(4), 38 (2002)

Photovoltaic

- Economy, ecology, philosophy, design, architecture.

- Sun studies, meteorology, landscape studies.

- Research & development:
  - Materials studies
  - Solar cell structure
  - Module, network, grid
  - Energy storage
  - Space solar

Characterization and monitoring.

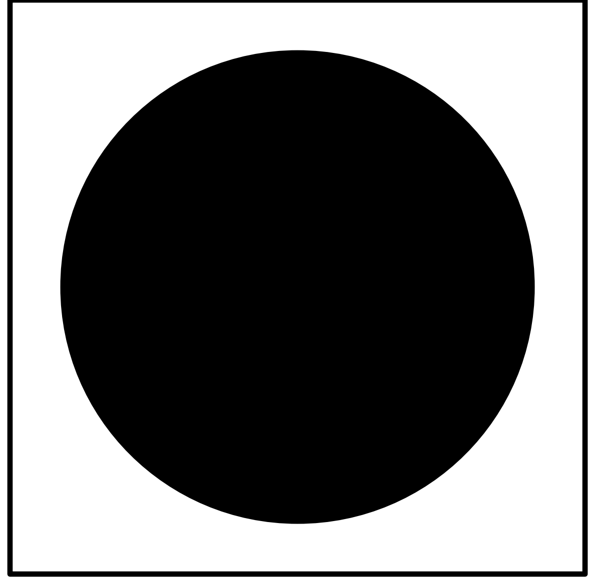
- Production:
  - Materials
  - Solar cell
  - Modules
  - Components

- Solar system utilization:
  - Installation
  - Maintenance
  - Disposal

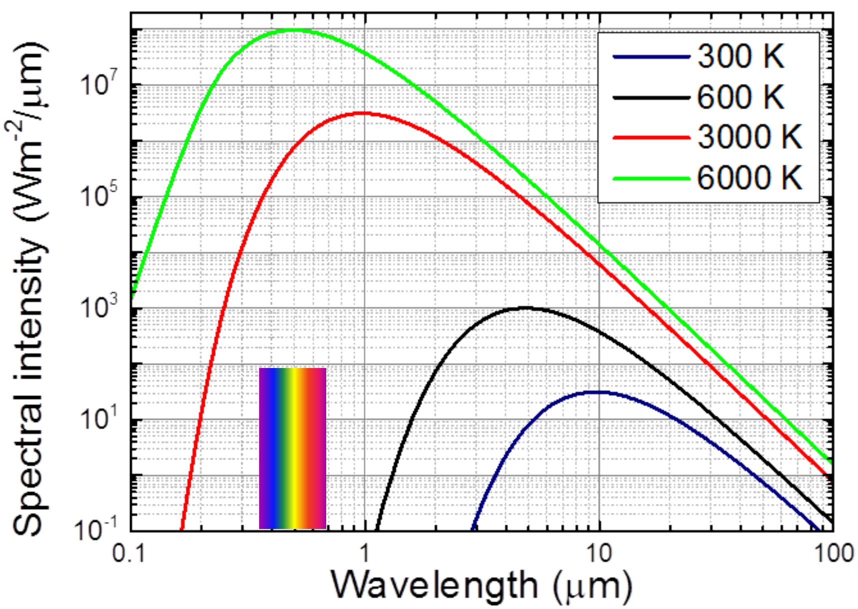
Planck's radiation law:

$$F(\lambda) = \frac{2\pi h c^2}{\lambda^5\left(\exp\left(\frac{hc}{k\lambda T}\right) - 1\right)}$$

where:
λ is the wavelength of light;
T is the temperature of the blackbody (K);
F is the spectral irradiance in $Wm^{-2}\mu m^{-1}$;
And h, c and k are constants



A blackbody absorbs all radiation incident on its surface and emits radiation based on its temperature.



The total power density from a blackbody is determined by integrating the spectral irradiance over all wavelengths which gives:

$$H = \sigma T^4$$

where $\sigma = 5.67 \times 10^{-8}\ J/m^2s\ K^4$ is the Stefan-Boltzmann constant and T is the temperature of the blackbody in Kelvin.

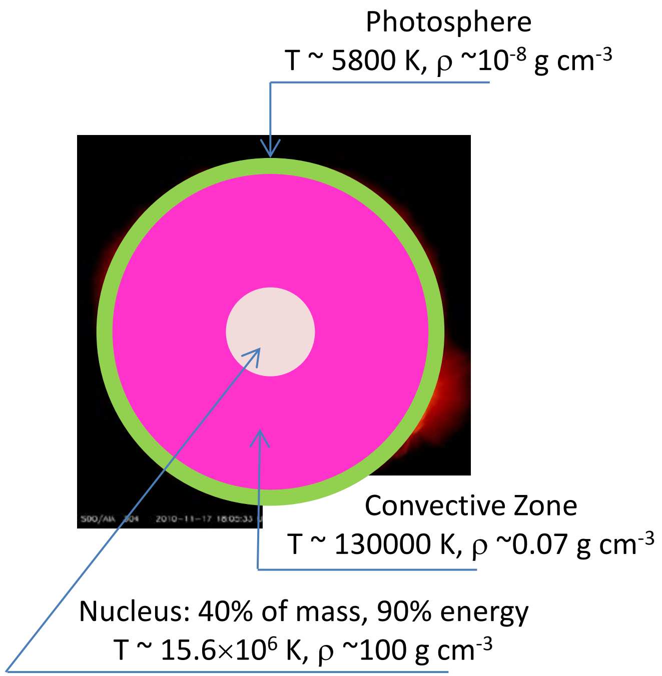
The wavelength where most of the power is emitted, the peak wavelength of the spectral irradiance can be obtained from Wien's Law:

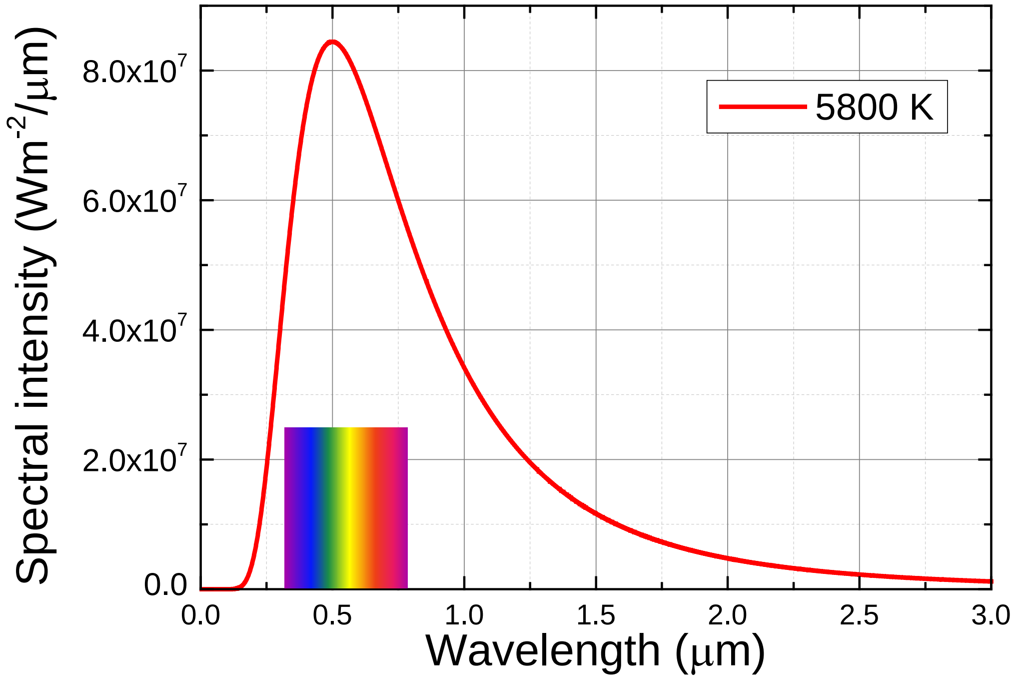
$$\lambda_P(\mu m) = 2900/T$$

http://www.space.com/
Plank, Annalen der Physik 4, 553 (1901) http://www.pveducation.org/

თეიმურაზ მჭედლიძე

Energy coming from the sun





For T=5800 K we will get

λ_p=0.5 µm

$H_{SUN} \approx 6.42 \times 10^7$ W/m^2

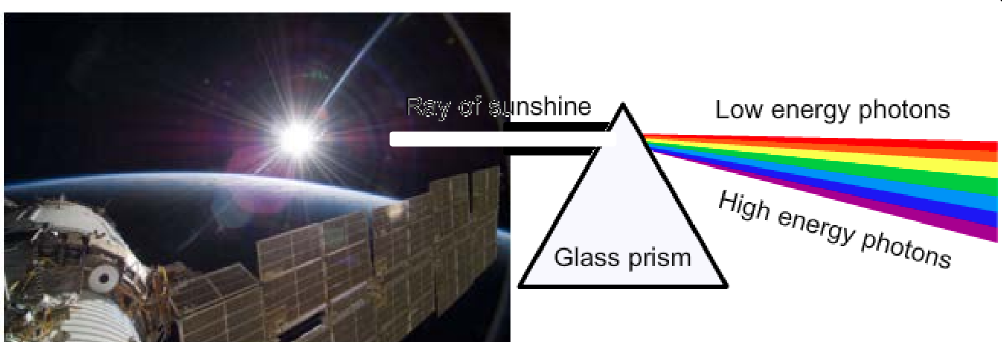
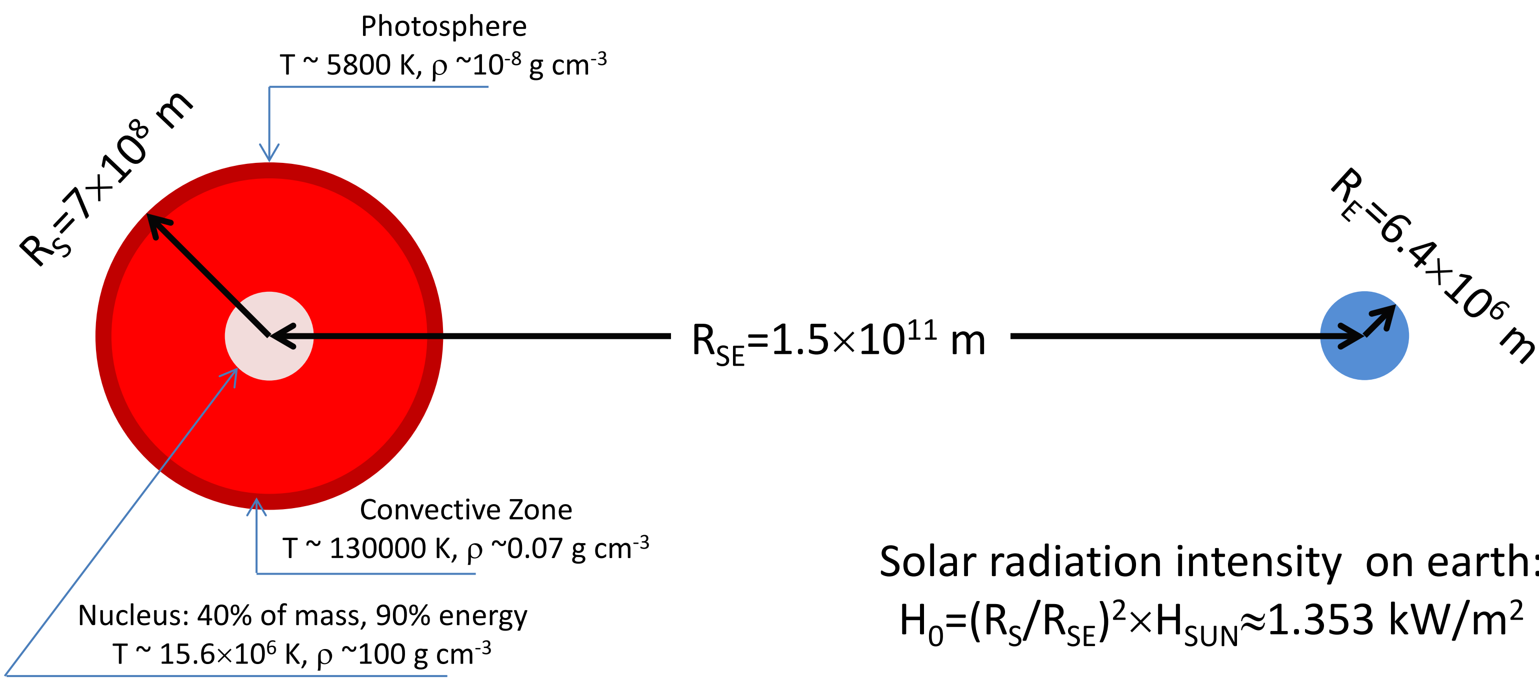


Image courtesy NASA

A. Goetzberger, Wittwer, Sonnenenergie, Teubner Studienbücher Physik
http://www.pveducation.org/

Energy coming from the sun



Solar radiation intensity on earth:

$H_0=(R_S/R_{SE})^2\times H_{SUN}\approx 1.353$ kW/m^2

Total Power emitted by the sun

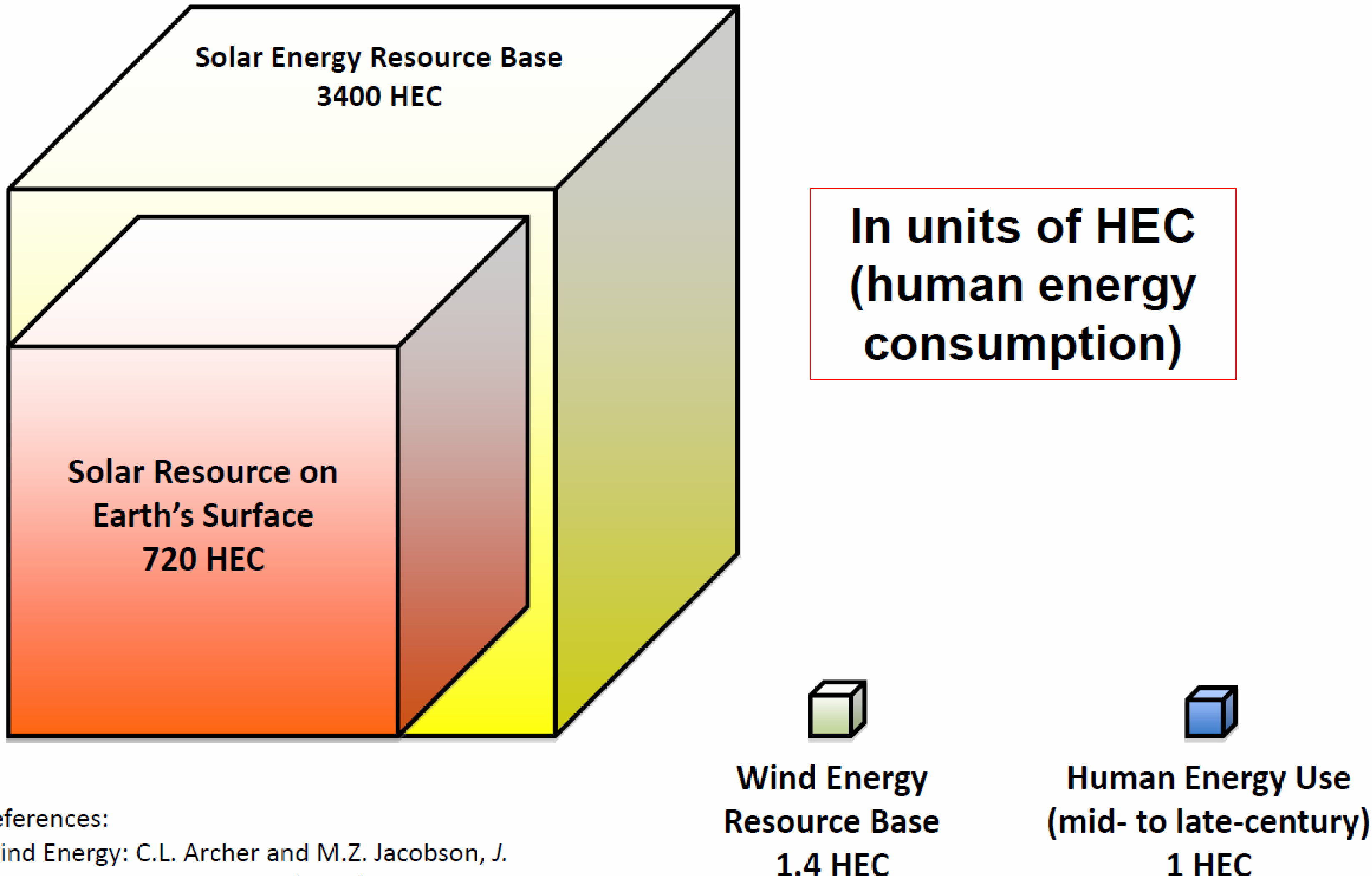
$P_{SUN} = H_{SUN} \times A_{SUN} = 9.5\times 10^{25}$ W

The value of the solar constant and its spectrum are fixed by ASTM as a standard value called "**air mass zero**" or **AM0**

თეიმურაზ მჭედლიძე

A. Goetzberger, Wittwer, Sonnenenergie, Teubner Studienbücher Physik

Solar resource

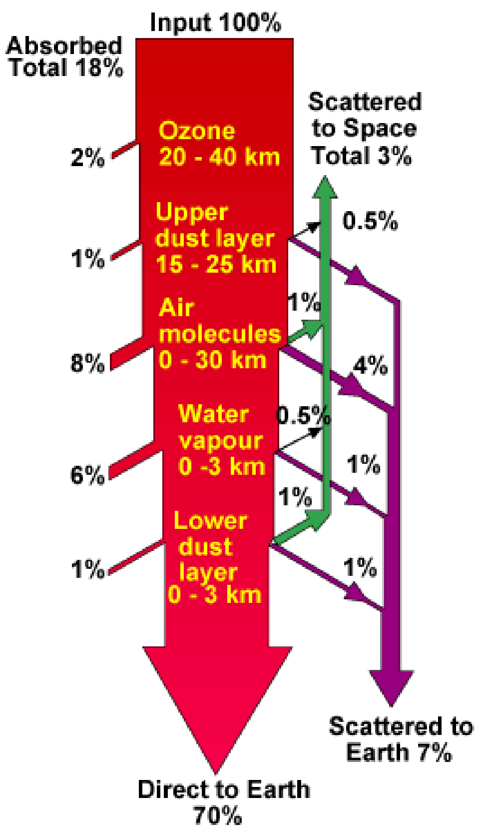


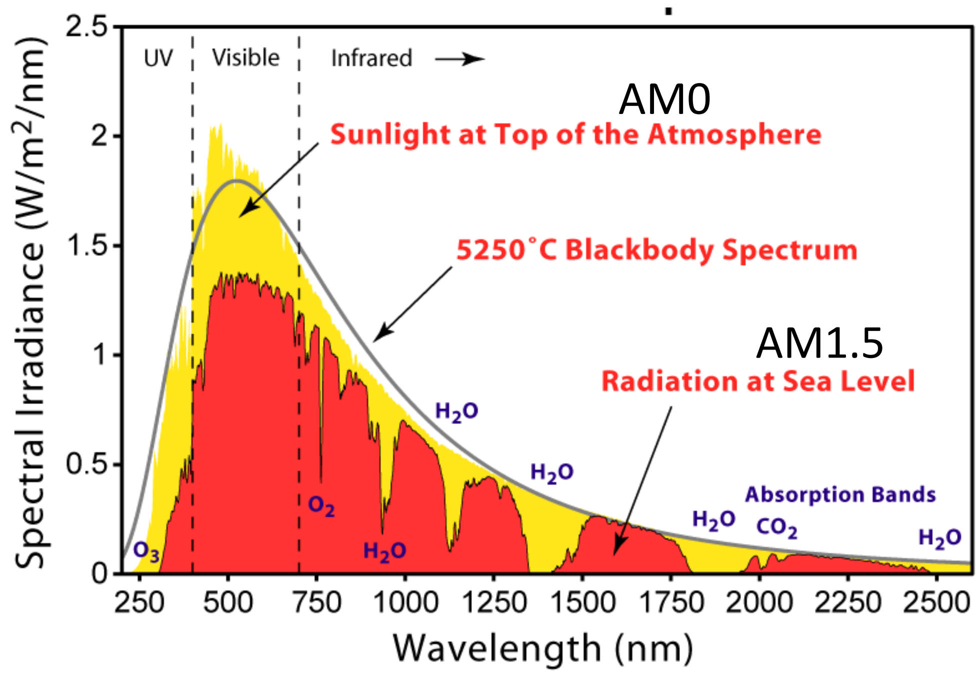
In units of HEC (human energy consumption)

References:
Wind Energy: C.L. Archer and M.Z. Jacobson, *J. Geophys. Res.* **110**, D12110 (2005).

Sun energy on the earth

- Seasonal variations due to elliptic orbit: $H=H_0(1+0.033\cos(360(n-2)/365))$
- Time of the day + Latitude of the location.

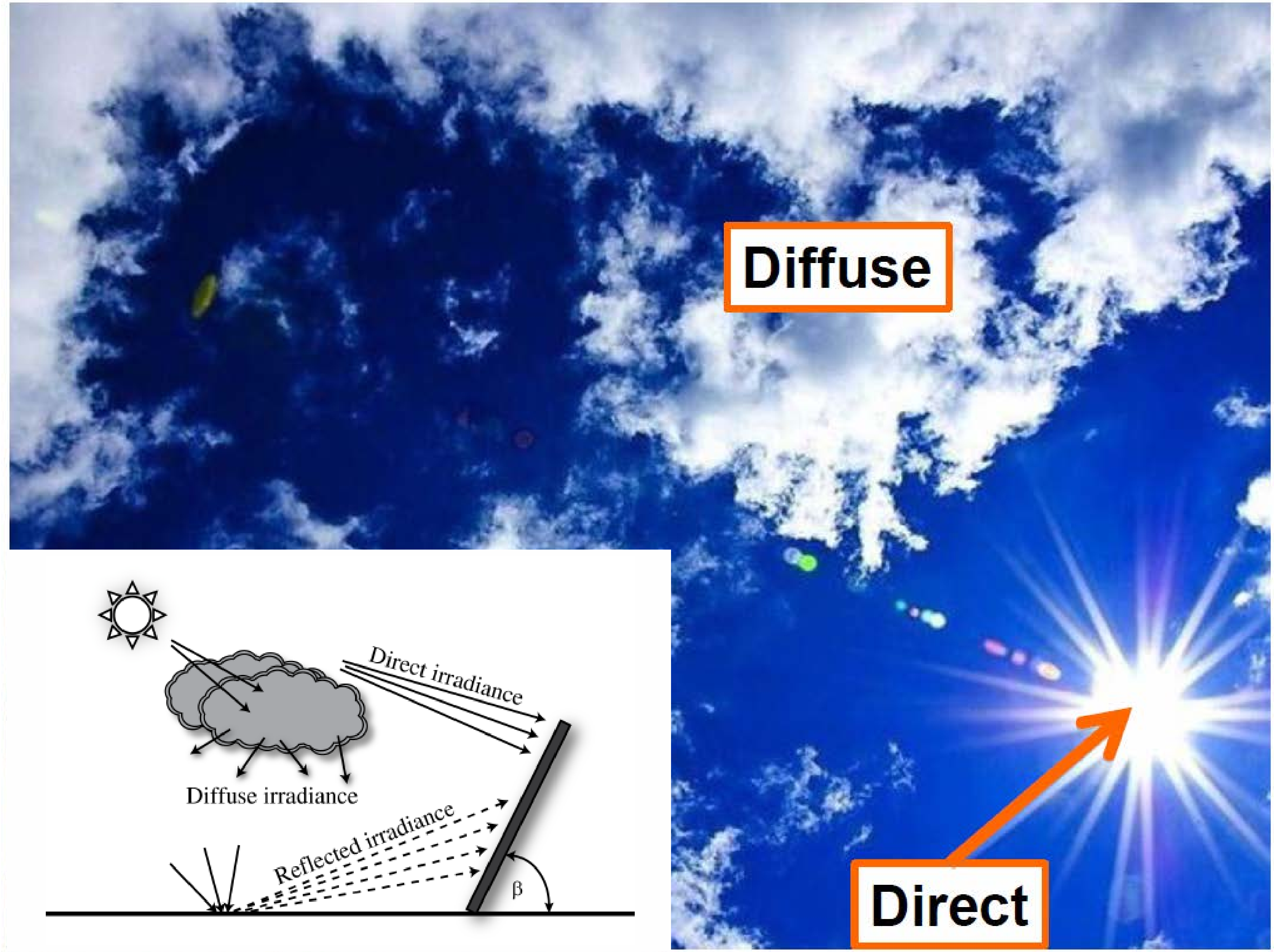




- Atmospheric effects, including absorption and scattering;
- Local variations in the atmosphere, such as water vapor, clouds, and pollution.

http://www.pveducation.org/
https://www.pvlighthouse.com.au

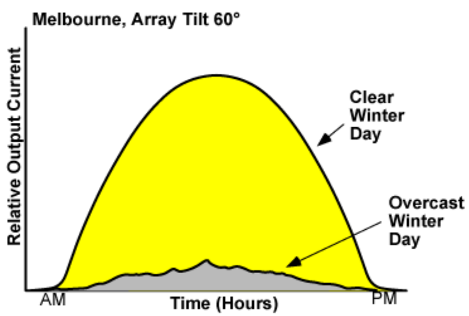
Direct, reflected and diffuse solar radiation



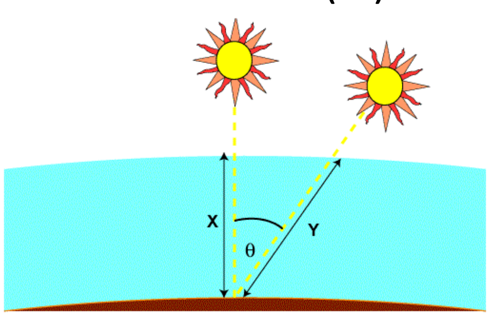
T. Buonassisi, MIT OpenCourseWare (2013). http://ocw.mit.edu
M. Culin, et ai., http://www.enhems-buildings.fer.hr/

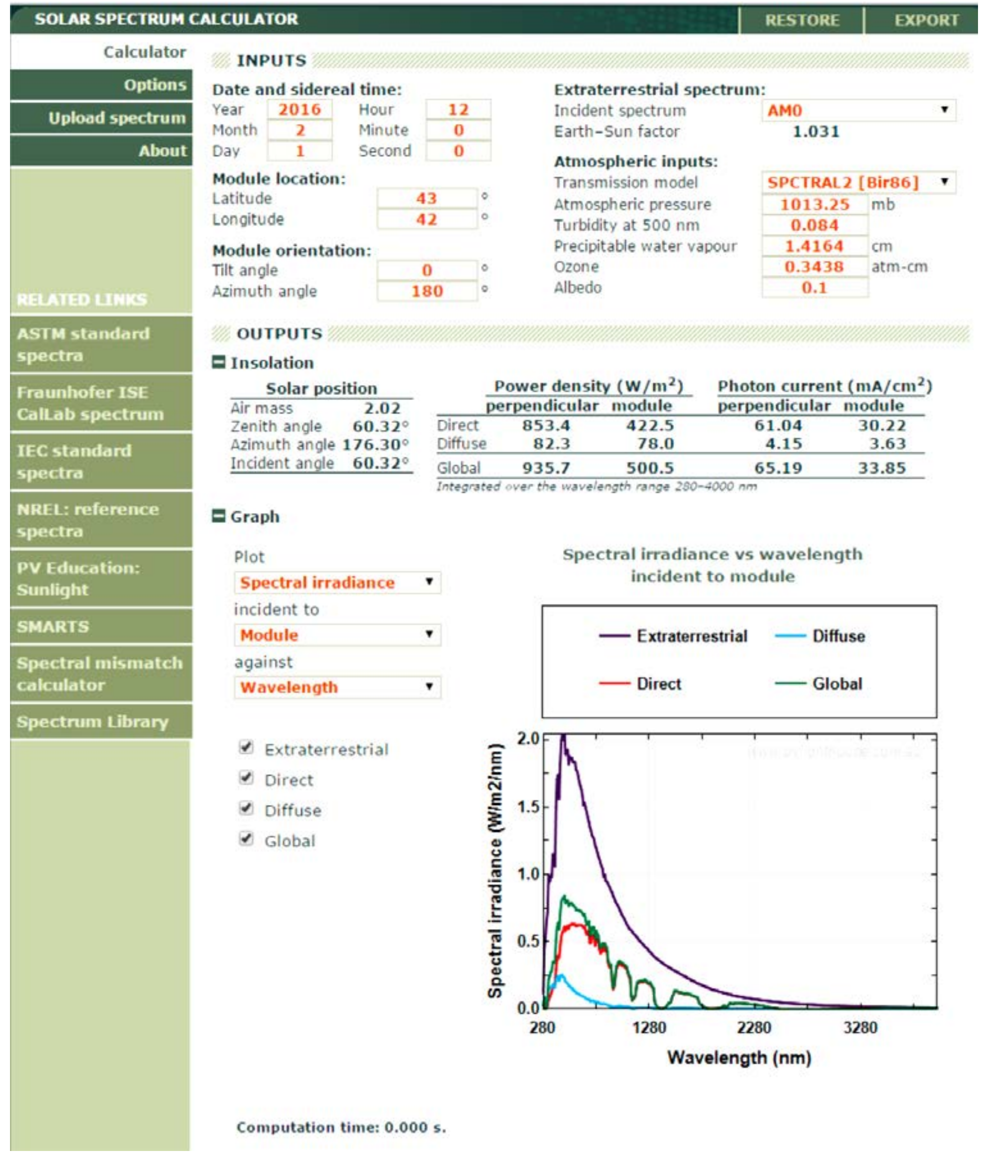
Solar spectra calculators

- Direct irradiation: from sun
- Diffuse Irradiation: sun irradiation scattered from particles in atmosphere (up to 10%, blue)
  - Rayleigh scattering (λ^{-4})
  - Mie scattering
- Effect of clouds:



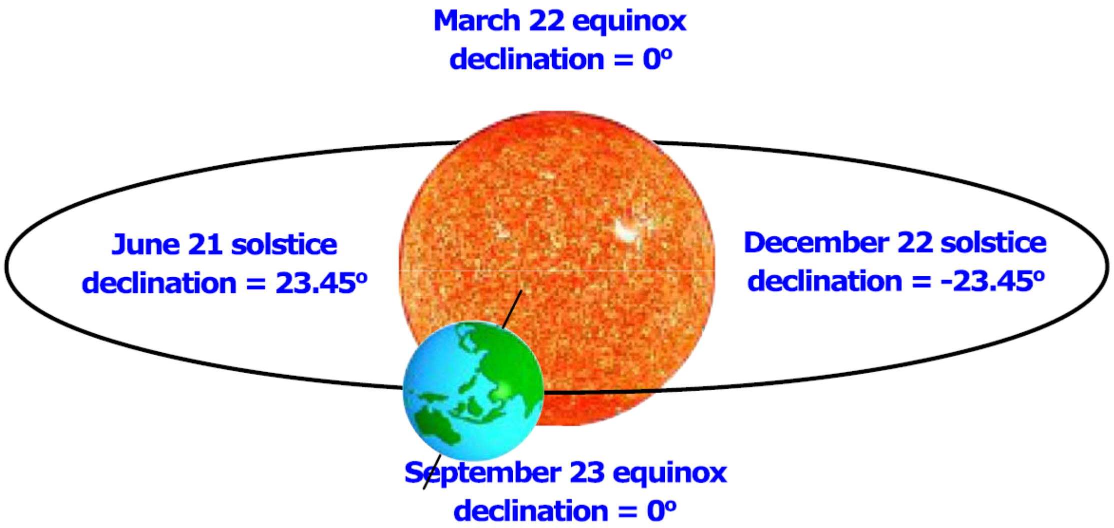
- Air mass: AM=$\cos^{-1}(\Theta)$

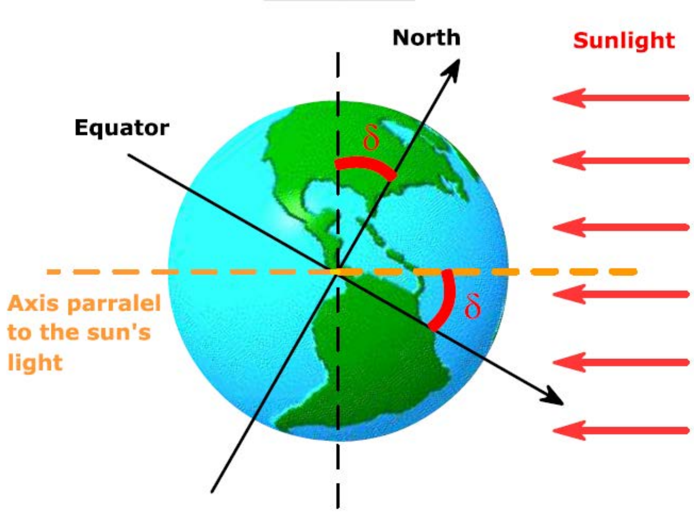




https://www.pvlighthouse.com.au/calculators/
http://www.pveducation.org/

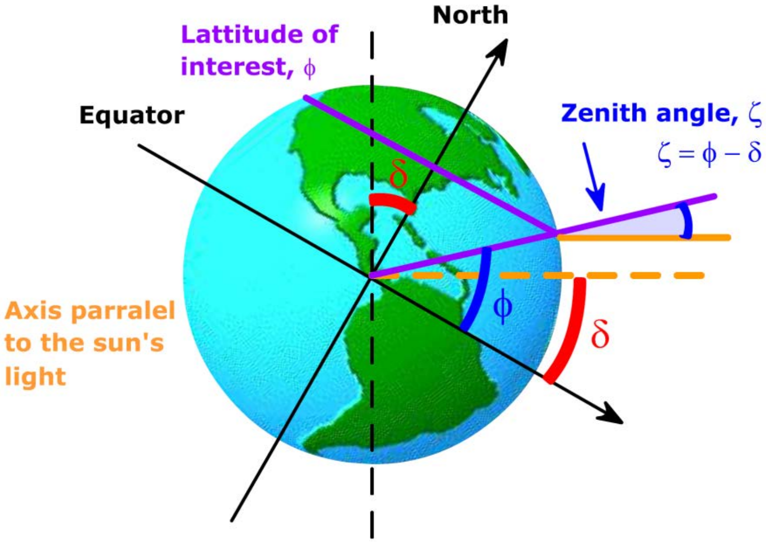
Motion of the earth



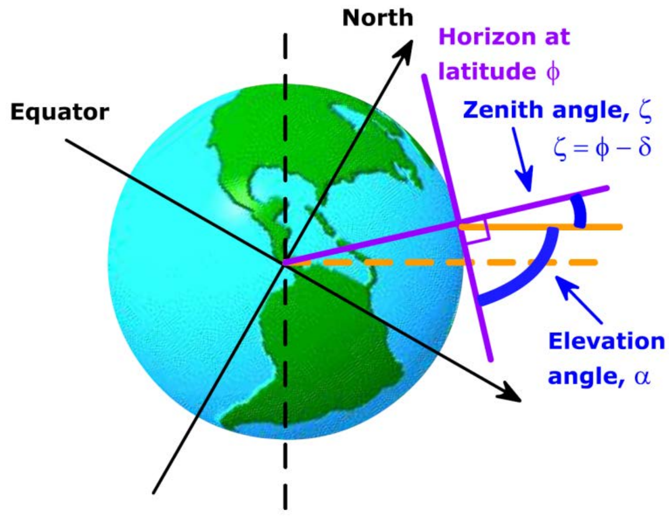


The tilt of the earth compared to the sun, the declination angle δ, depends on the season. The maximum angle occurs at summer solstice in northern hemisphere and at winter solstice in southern hemisphere

More angles

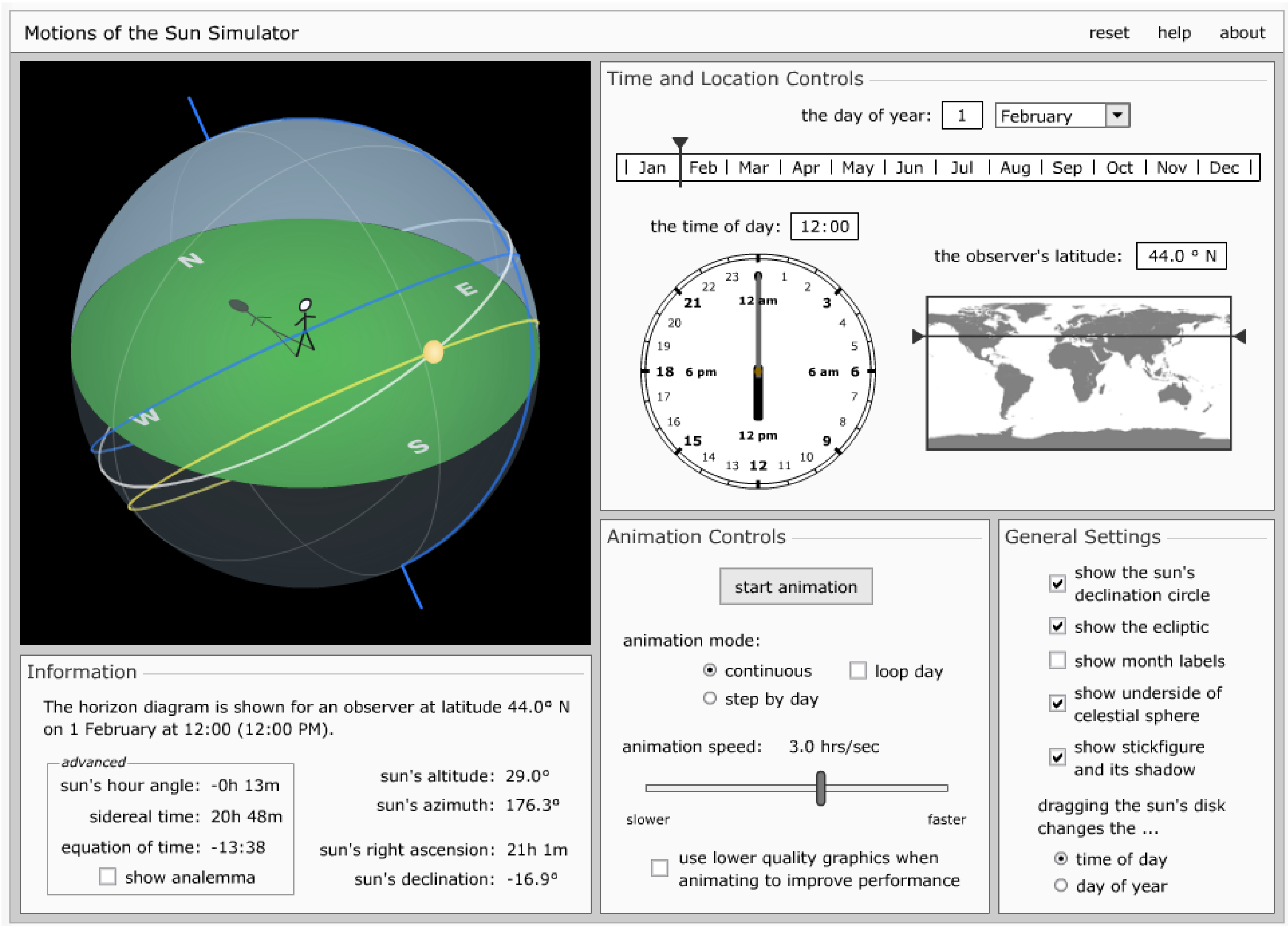


The zenith angle, ξ, at solar noon is defined as the angle between the incident sunlight and the particular location and is given by (ϕ-δ).



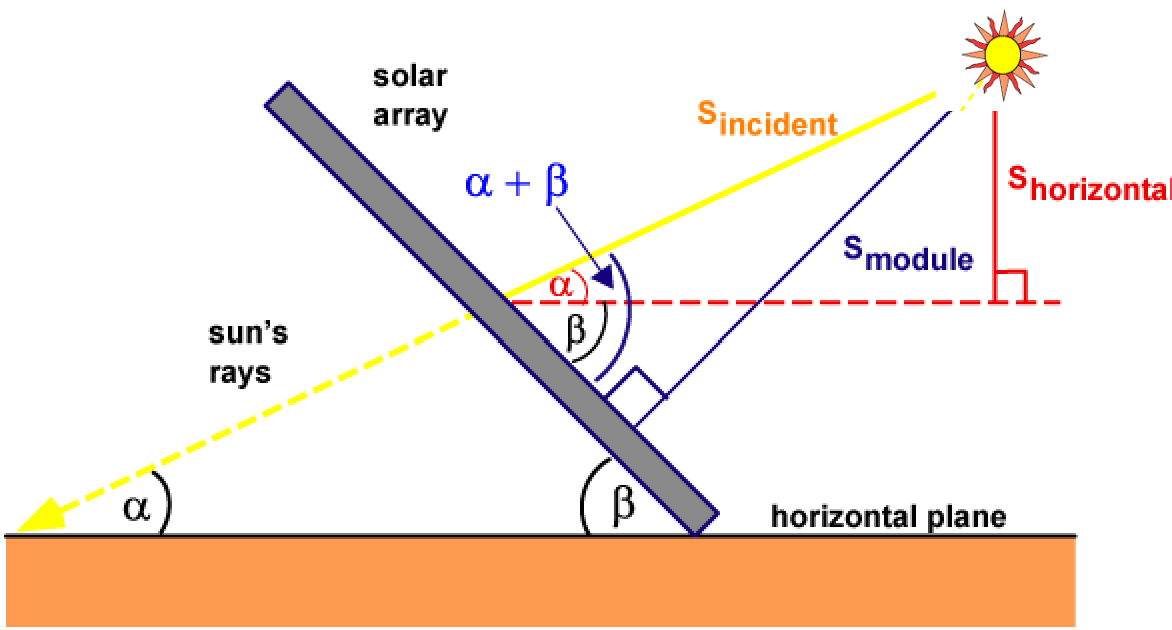
The elevation or altitude angle, α, is defined from the horizontal plane and is given by 90°- zenith angle, or 90° - (ϕ - δ).

Motions by the sun simulator



http://astro.unl.edu/naap/motion3/animations/sunmotions.html

Solar radiation on a tilted surface



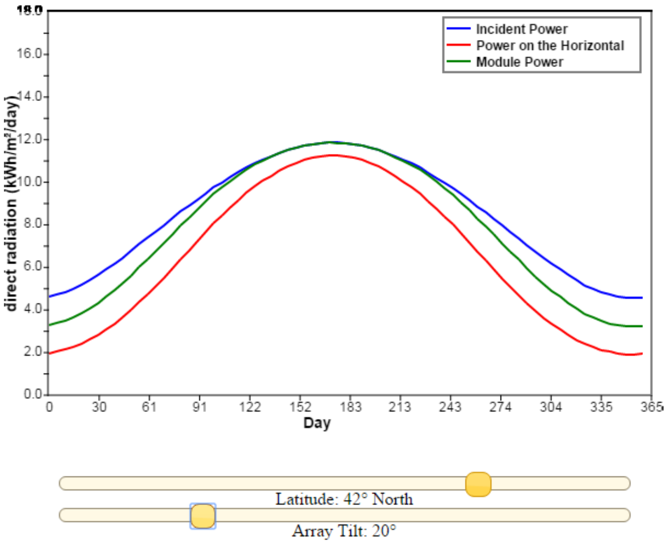
Power density, S incident on a PV module with tilt angle β:

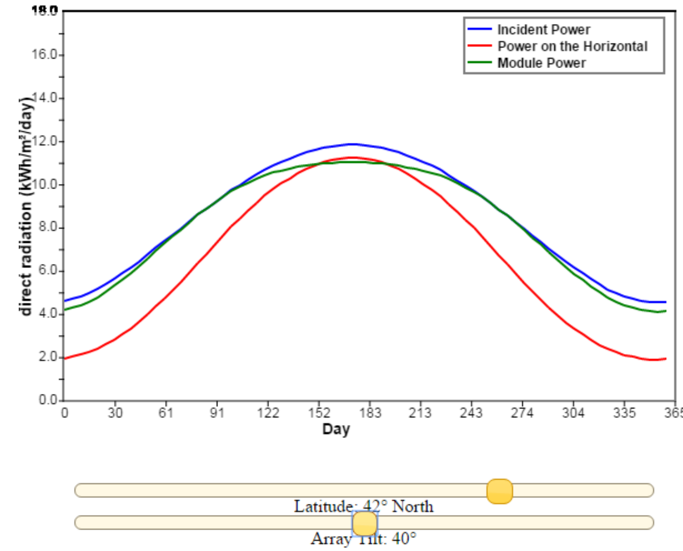
$S_{module} = S_{horizontal} \; \sin(\alpha+\beta)/\sin\alpha$

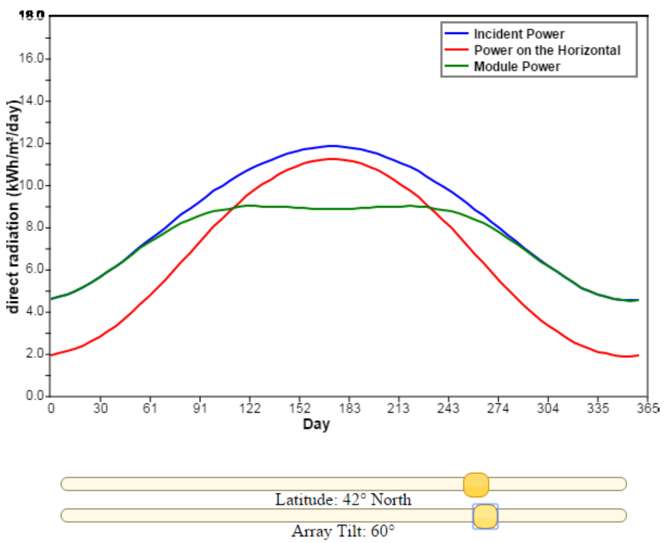
The elevation angle: $\alpha = 90° - \Phi \pm \delta$ with Φ : latitude; δ: declination

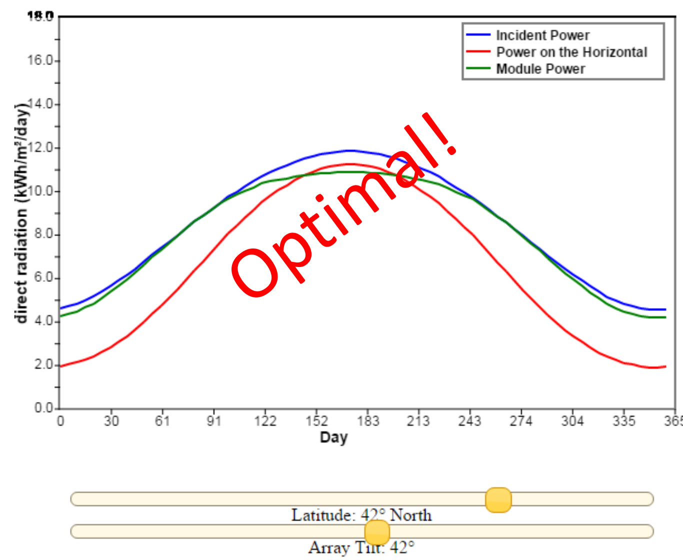
δ depends on the day of year, best tilt angle $\beta = \Phi$

Module power over the year

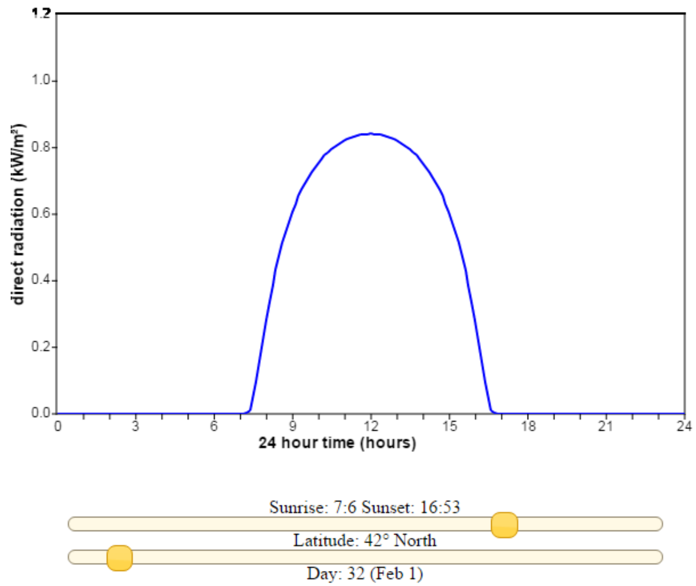


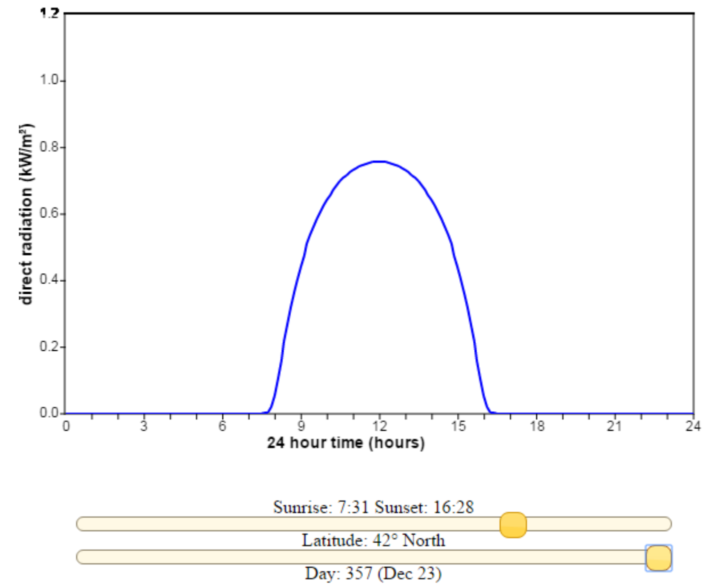


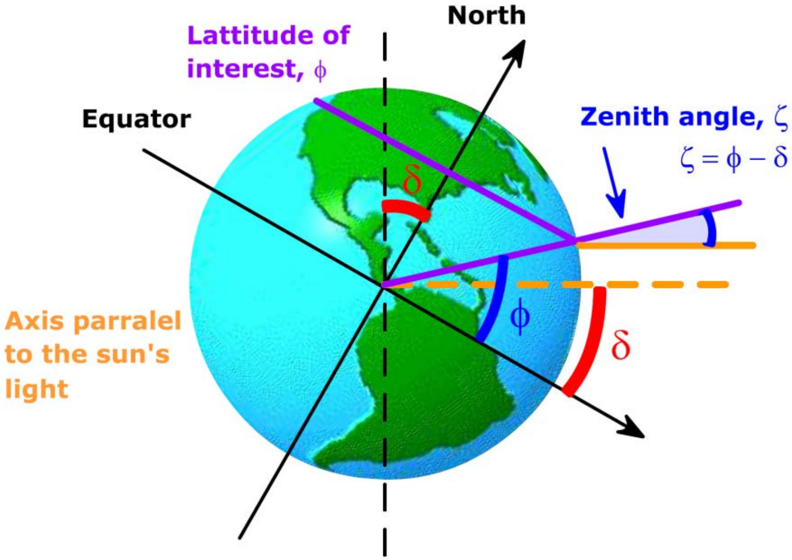




Calculation of Solar Insolation







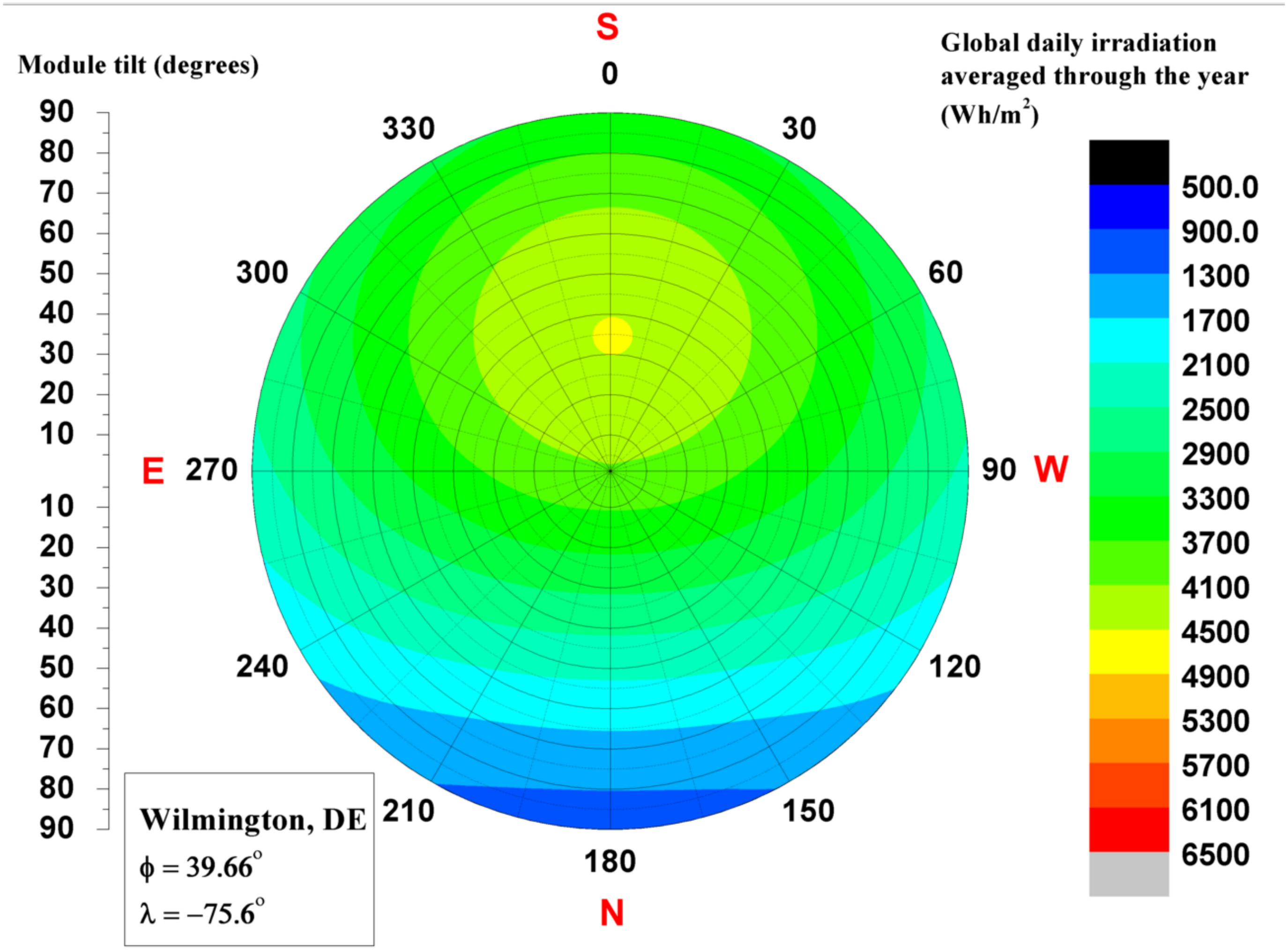
$$Sunrise = 12 - \frac{1}{15^0}\cos^{-1}\left(\frac{-\sin\varphi\sin\delta}{\cos\varphi\cos\delta}\right)$$

$$Sunset = 12 + \frac{1}{15^0}\cos^{-1}\left(\frac{-\sin\varphi\sin\delta}{\cos\varphi\cos\delta}\right)$$

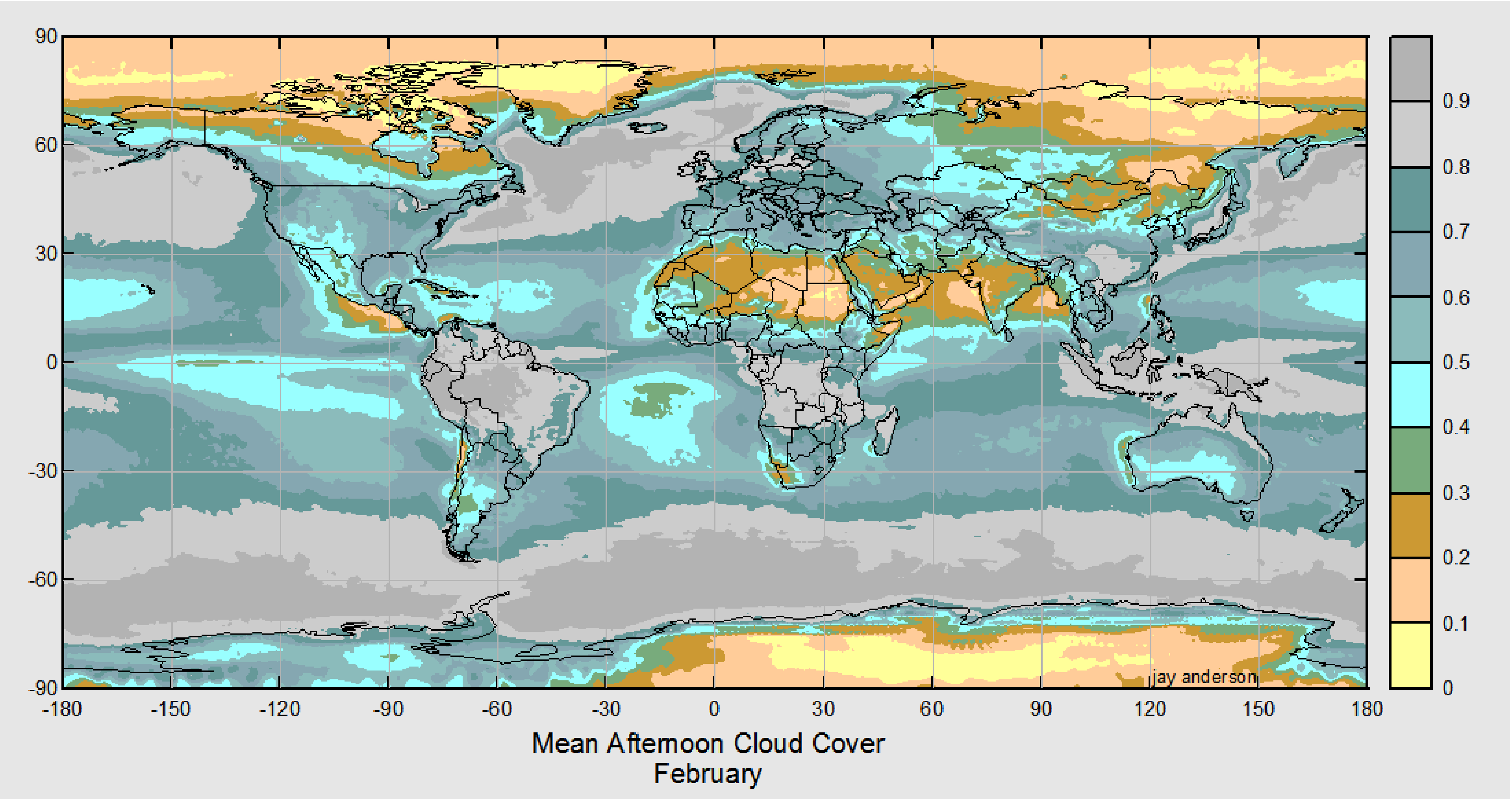
$$I_D = 1.353 \times 0.7^{\left(AM^{0.678}\right)}$$

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

The contour diagram of the global daily irradiation averaged through the year

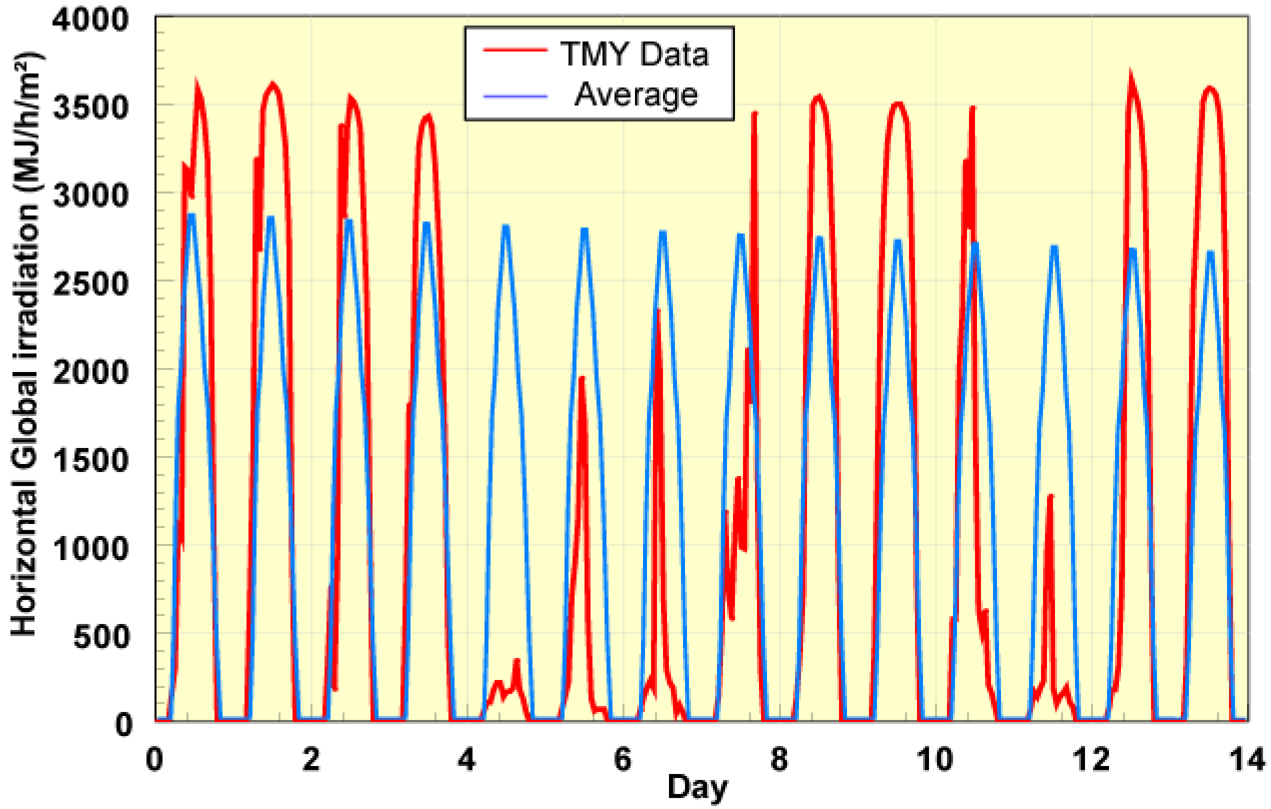


Cloud Cover Data



http://home.cc.umanitoba.ca/~jander/clouds/globalclouds.html

Typical Meteorological Year Data (TMY)



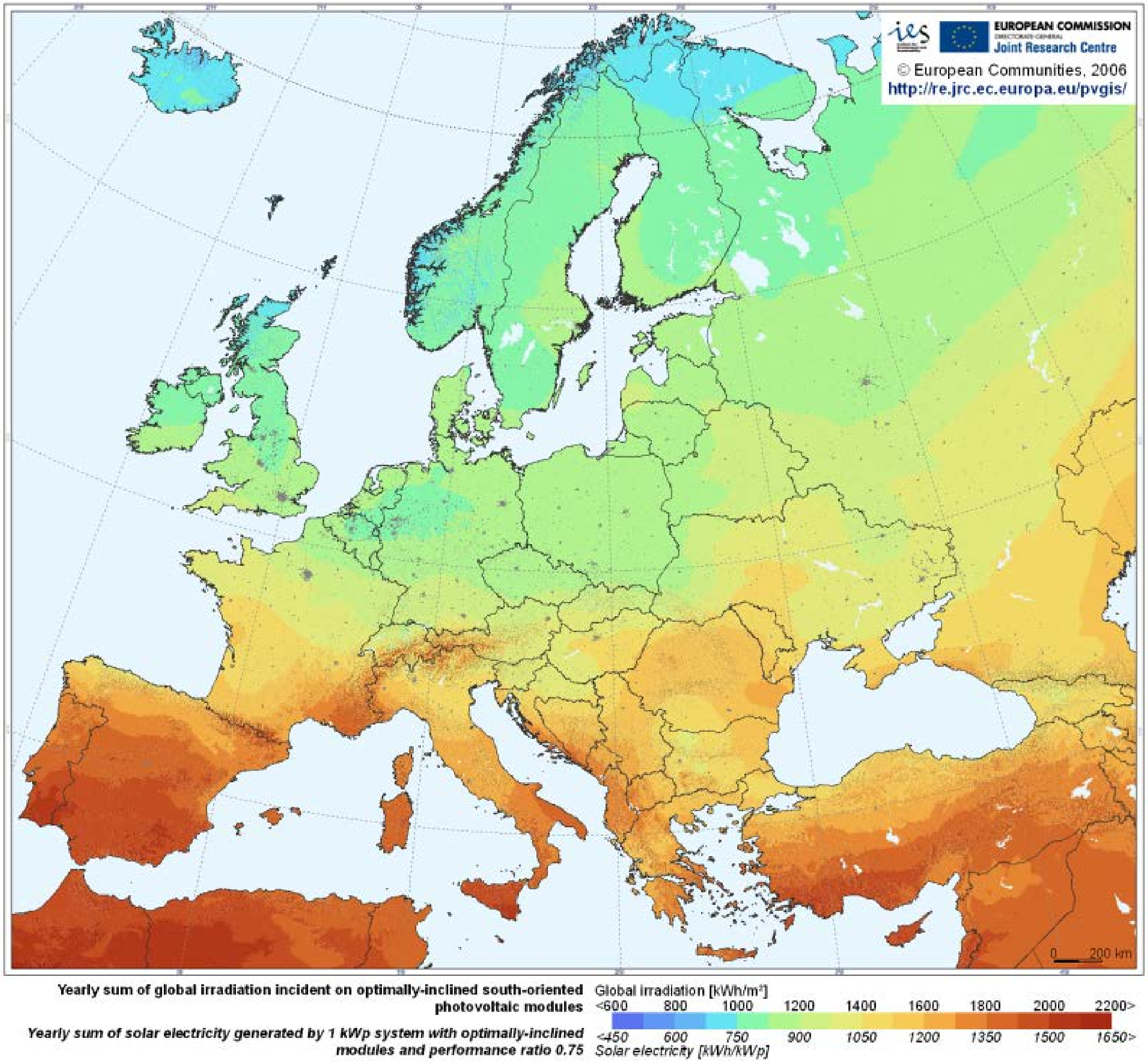
Solar radiance: [kWh/m^2]

Solar insolation: total amount of solar energy received during a specific time period [kWh/m^{2}day]

Peak sun hours: average daily solar insolation in units of kWh/m^2

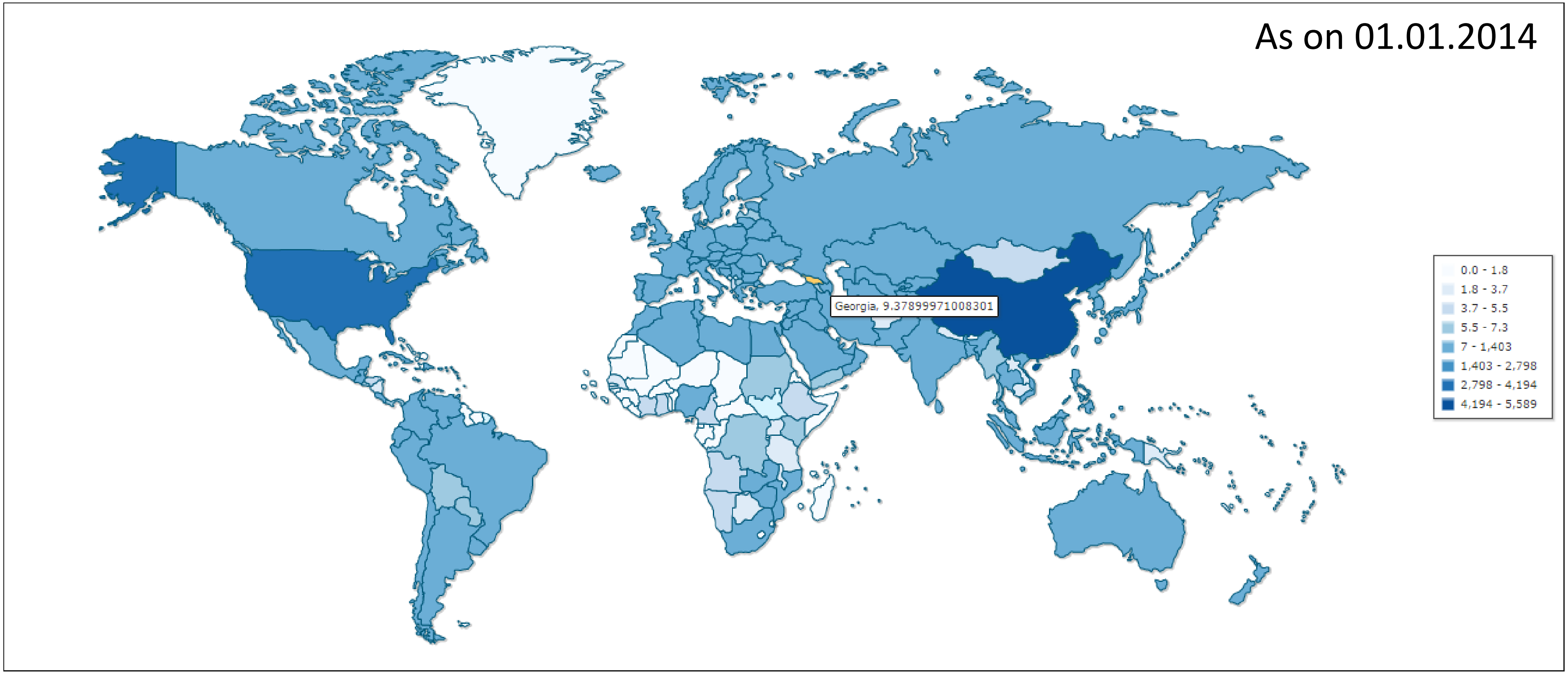
Watt peak (W_p): under test conditions of AM1.5 (1000W/m^2) and 25°C a module produces an electrical output of e,g. 10kW, this is given as 10kW_p.

Photovoltaic Solar Electricity Potential in European Countries



http://sunbird.jrc.it/pvgis/

Electricity consumption in the world

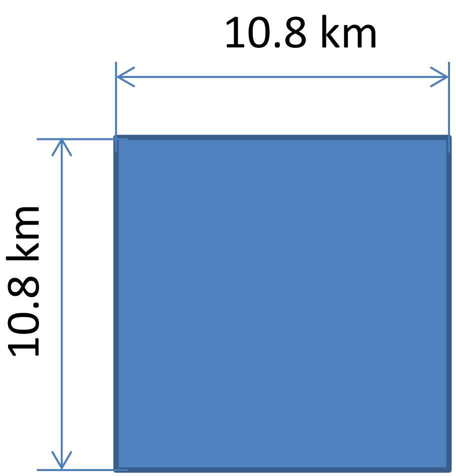


http://www.indexmundi.com/

For the whole Georgia

$$Area\ required = \frac{Energy\ consumption\ (\frac{kWh}{year})}{Energy\ resource\ \left(\frac{kWh}{m^2 day}\right) \times 365\ (day) \times Efficiency} =$$

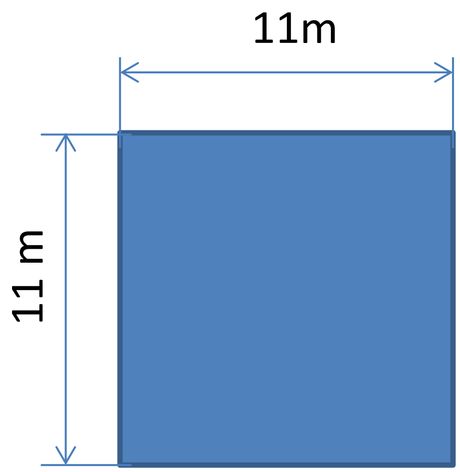
$$= \frac{9.38{\cdot}10^9\ kWh/year}{3.68\,\frac{kWh}{m^2 day} \times 365\ day \times 0.06} = 1.16{\cdot}10^8\ m^2$$



For a single house

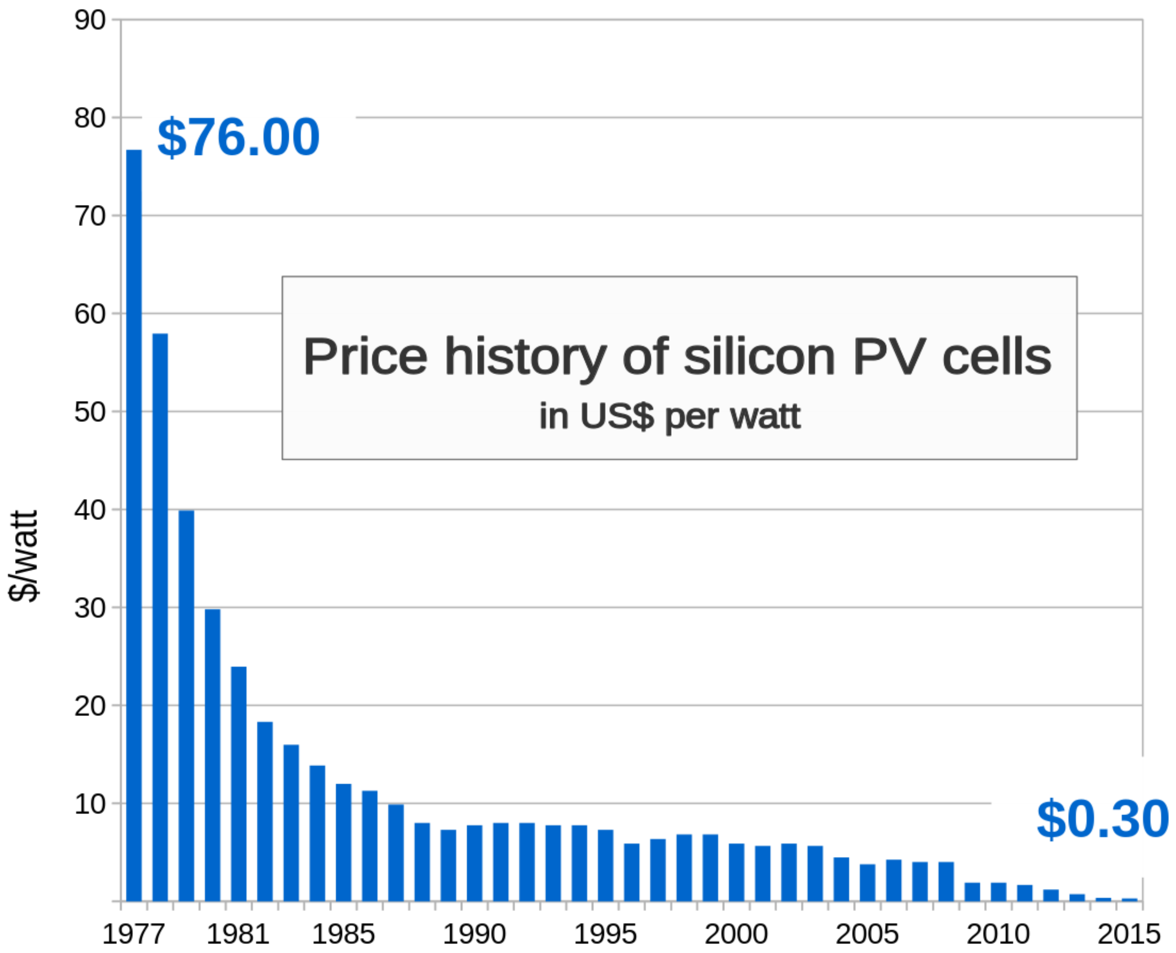
$$Area\ required = \frac{Energy\ consumption\ (\frac{kWh}{year})}{Energy\ resource\ \left(\frac{kWh}{m^2 day}\right) \times 365\ (day) \times Efficiency} =$$

$$= \frac{10^5\ kWh/year}{3.68\frac{kWh}{m^2 day} \times 365\ day \times 0.06} = 124\ m^2$$



თეიმურაზ მჭედლიძე

Price of Si solar cells



Source: Bloomberg New Energy Finance & pv.energytrend.com

Price of necessary Si solar cells

$$Price(\$) = \frac{Required\ Power\ (W) \times price\ (\$\ per\ WP)}{W/W_P} =$$

$$= \frac{9.38 \cdot 10^{12}\ \left(\frac{Wh}{year}\right) \times 0.3 (\frac{\$}{W_P})}{365\ day \times 24\ hour \times 0.6\ (\frac{W}{W_P})} \approx 0.535 \cdot 10^9\ \$$$

Georgia Budget (2013): Budget: revenues: 4.834×10^9 $

Price for a single house ≈ 6000 $

http://www.indexmundi.com/

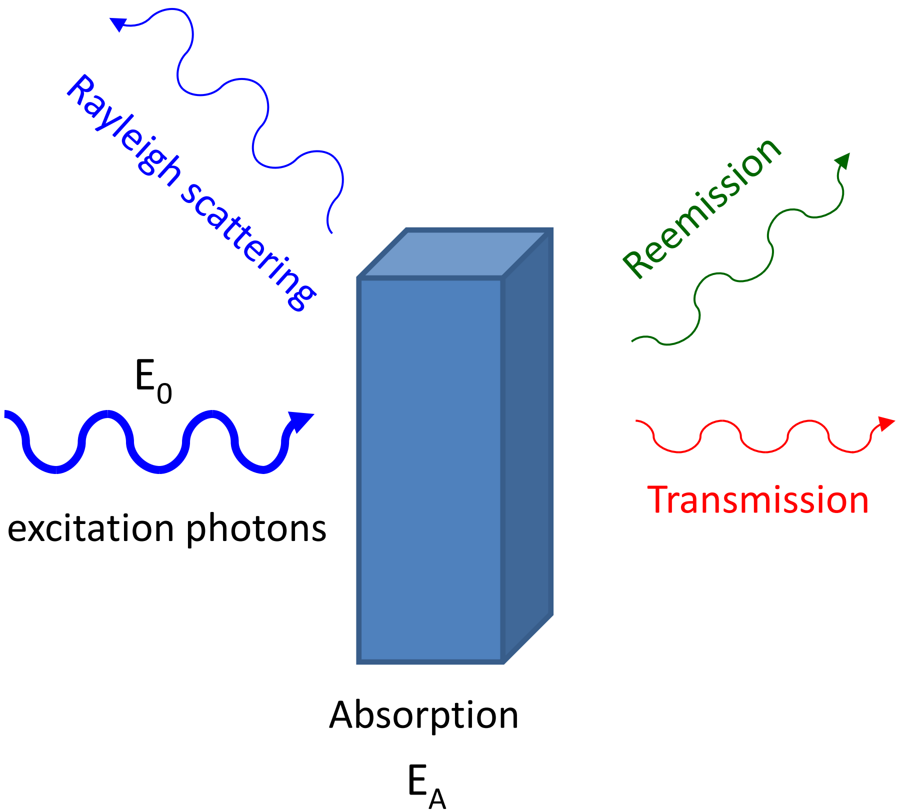
დასკვნები

- მზის ენერგიის რესურსი 700-ჯერ აღემატება მთელი დედამიწის მოსახლეობის თანამედროვე მოთხოვნილობას ელექტროენერგიაში.
- მზის პირდაპირი (უშუალო) გამოსხივების გარდა, არსებობს დიფუზიური და არეკლილი გამოსხივება, რომელიც აგრთვე შეიძლება გამოყენებულ იქნას ენერგიის მოსაპოვებლად.
- შესაძლებელია განვახორციელოთ საკმაოდ კარგი სიზუსტის გამოთვლები იმ ენერგიისა რომლის "მოპოვება" შესაძლებელია მზის გამოსხივებიდან. ასეთ გამოთვლებზე დაყრნობით შედგენილია მზის დასხივების დღიური და წლიური რექები.
- აგრეთვე შეიძლება დავითვალოთ მზის პანელების ოპტიმალური ორიენტაცია და საჭირო რაოდენობა.
- საქართველოსთვის მზის ენერგიის გამოყენებას საკმაოდ კარგი პერსპექტივები გააჩნია.

ლექცია II: მზის ენერგიის გარდაქმნა ელექტრობად ნახევარგამტარების საშუალებით.

- გამოსხივების შთანთქმა ნახევარგამტარებში;
- ეფექტურობის ლიმიტი;
- დენის მატარებლების გენერაცია ფოტონების შთანთქმის შედეგად;
- ენერგიის დანაკარგები; ბრძოლა მაღალი ეფექტურობისათვის;
- ფოტოვოლტაიკური ელემენტების ისტორია.

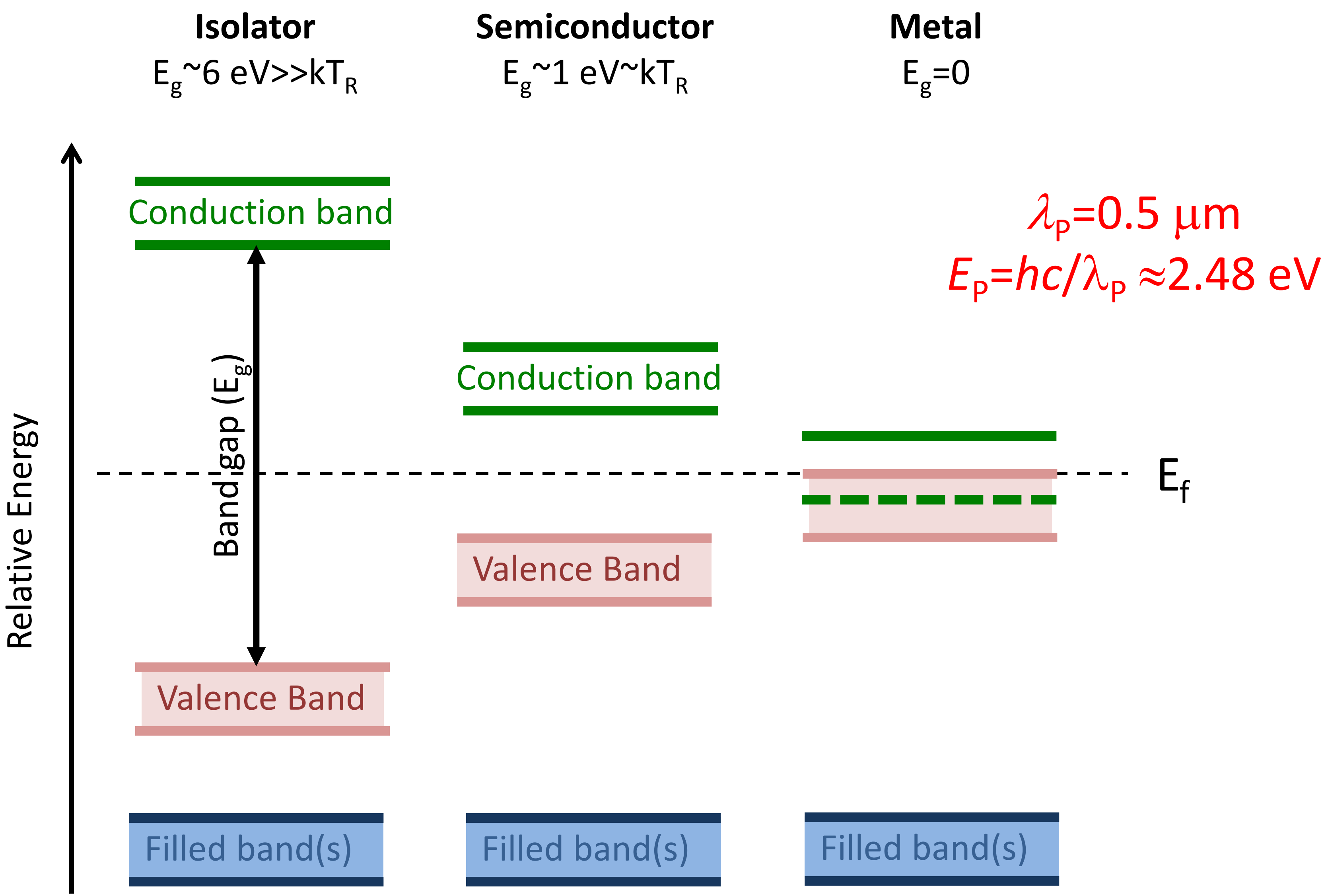
Interaction of photons with matter



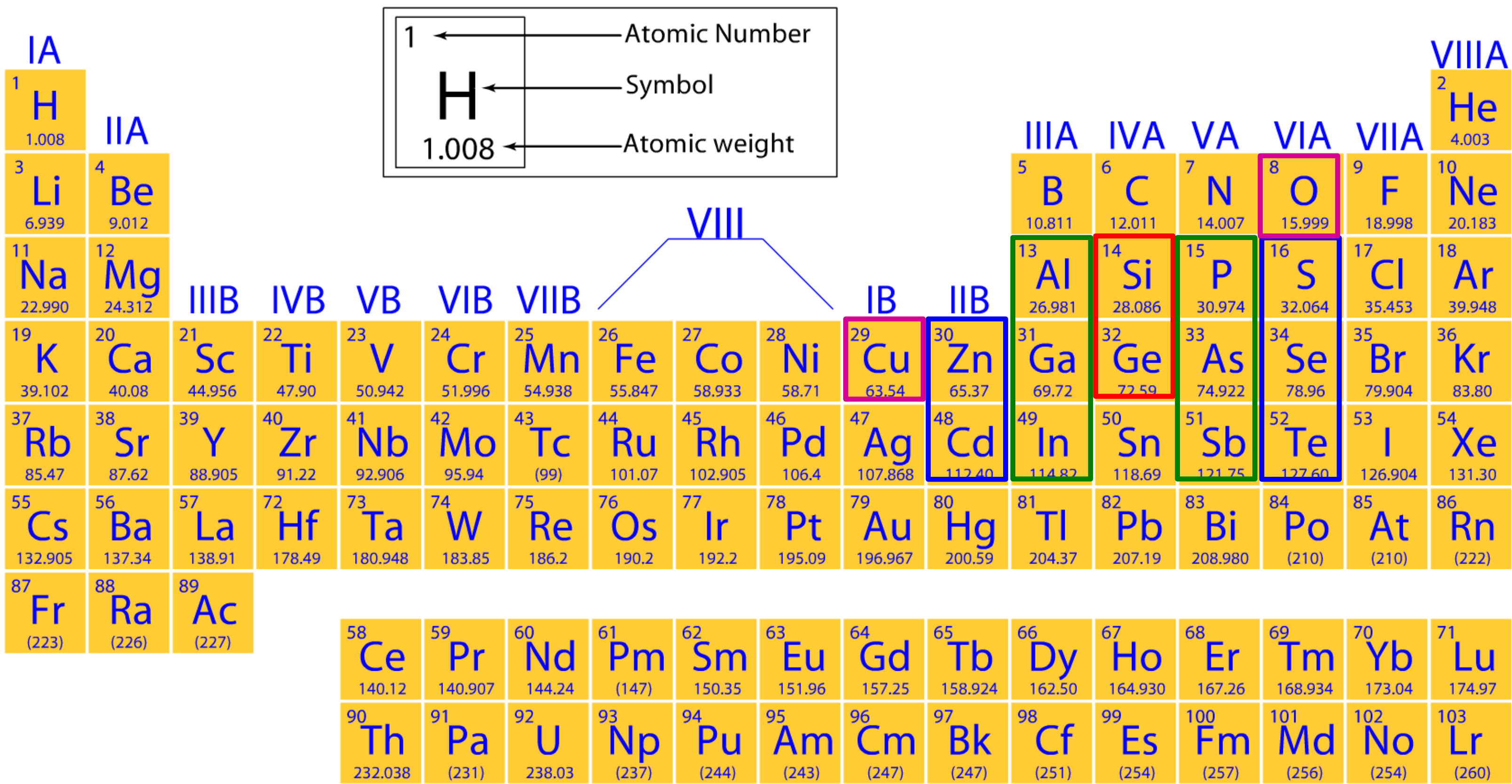
- **Transmission**: "untouched" photons, $\lambda_{in}=\lambda_{out}$
- **Rayleigh scattering**: elastic scattering, no change in wavelength, $\lambda_{in}=\lambda_{out}$
- **Reemission:** inelastic (Raman) scattering, Photoluminescence , $\lambda_{in}<\lambda_{out}$
- **Absorption (E_A)**.

$$E_0 > E_A > E_{el}$$
$$\eta = E_{el}/E_0$$

Energy band gaps in materials



Periodic table of elements



Group IV (Si, Ge)

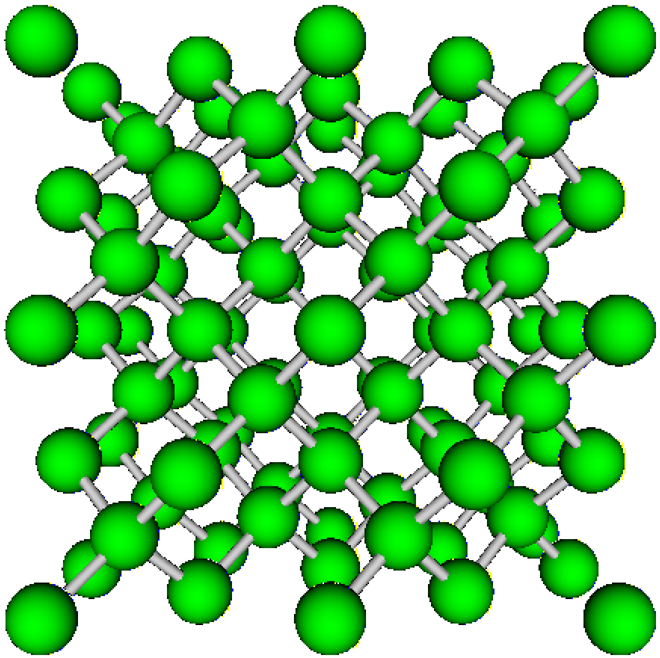
Group III-V (GaAs, InP,…)

Group II-VI (ZnTe, CdS, …)

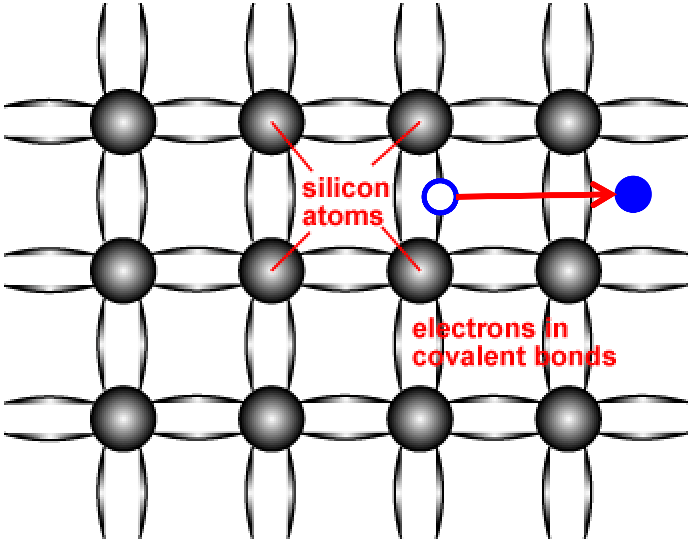
Compound, Alloy ($Al_xGa_{(1-x)}As$, CuO, Si_XGe_{1-X}…)

თეიმურაზ მჭედლიძე

Silicon: atomic structure

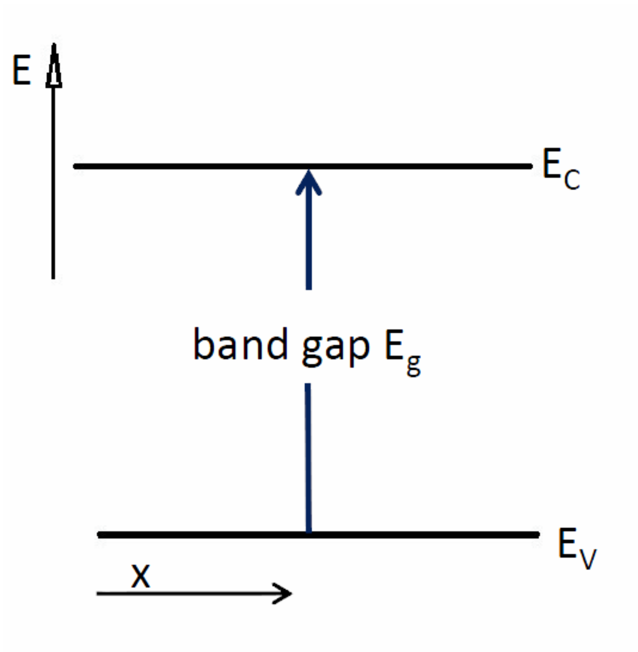


Diamond structure
Si, Ge

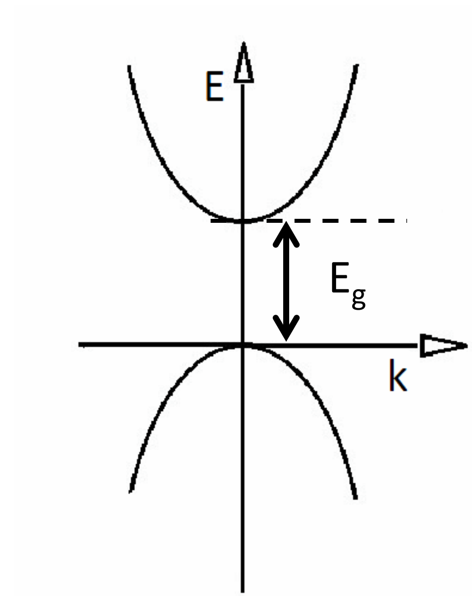


2D - representation

Energy band diagram, band structure

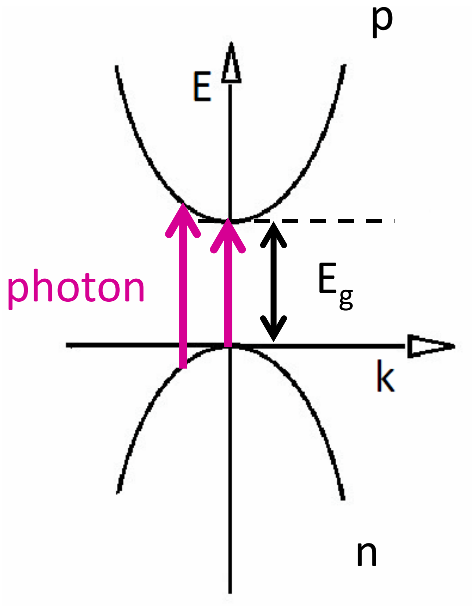


energy band digram E(x)



band structure E(k)
dispersion relation

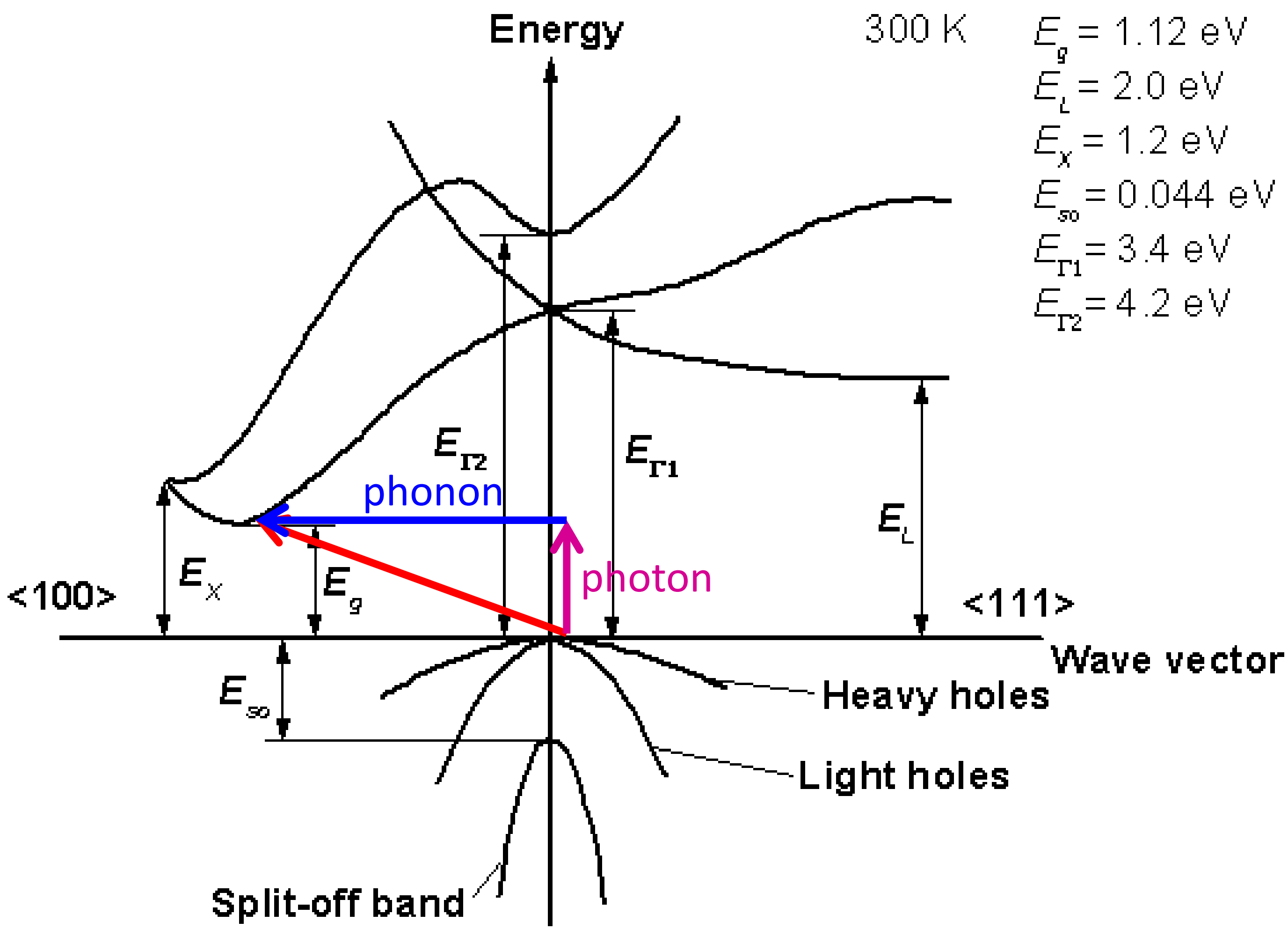
Photon absorption: conservation rules



Energy: $\hbar\omega_{phot} = E_g + \frac{\hbar^2 k_n^2}{2m_n} + \frac{\hbar^2 k_p^2}{2m_p} \pm \hbar\omega_{phon}$

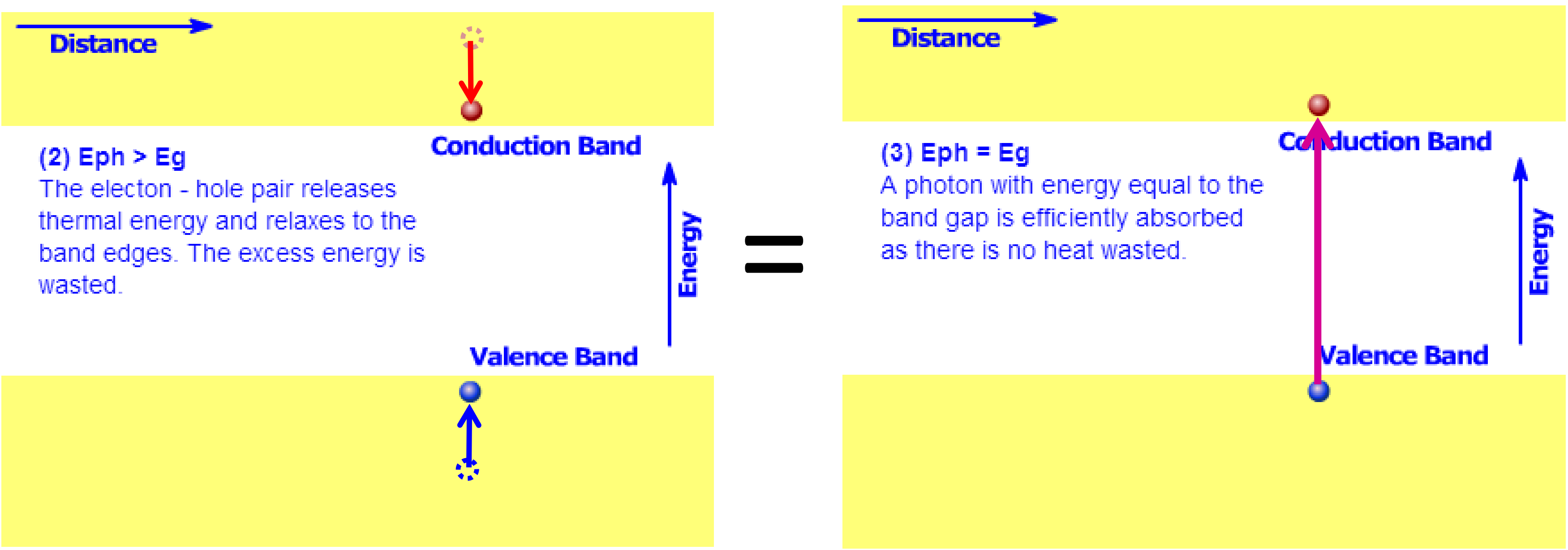
Momentum: $\hbar\vec{k}_{phot} = \hbar(\vec{k}_n + \vec{k}_p) + \hbar\vec{k}_{phon}$

Formation of electron-hole pair by photon



Formation of electron-hole pair by photon

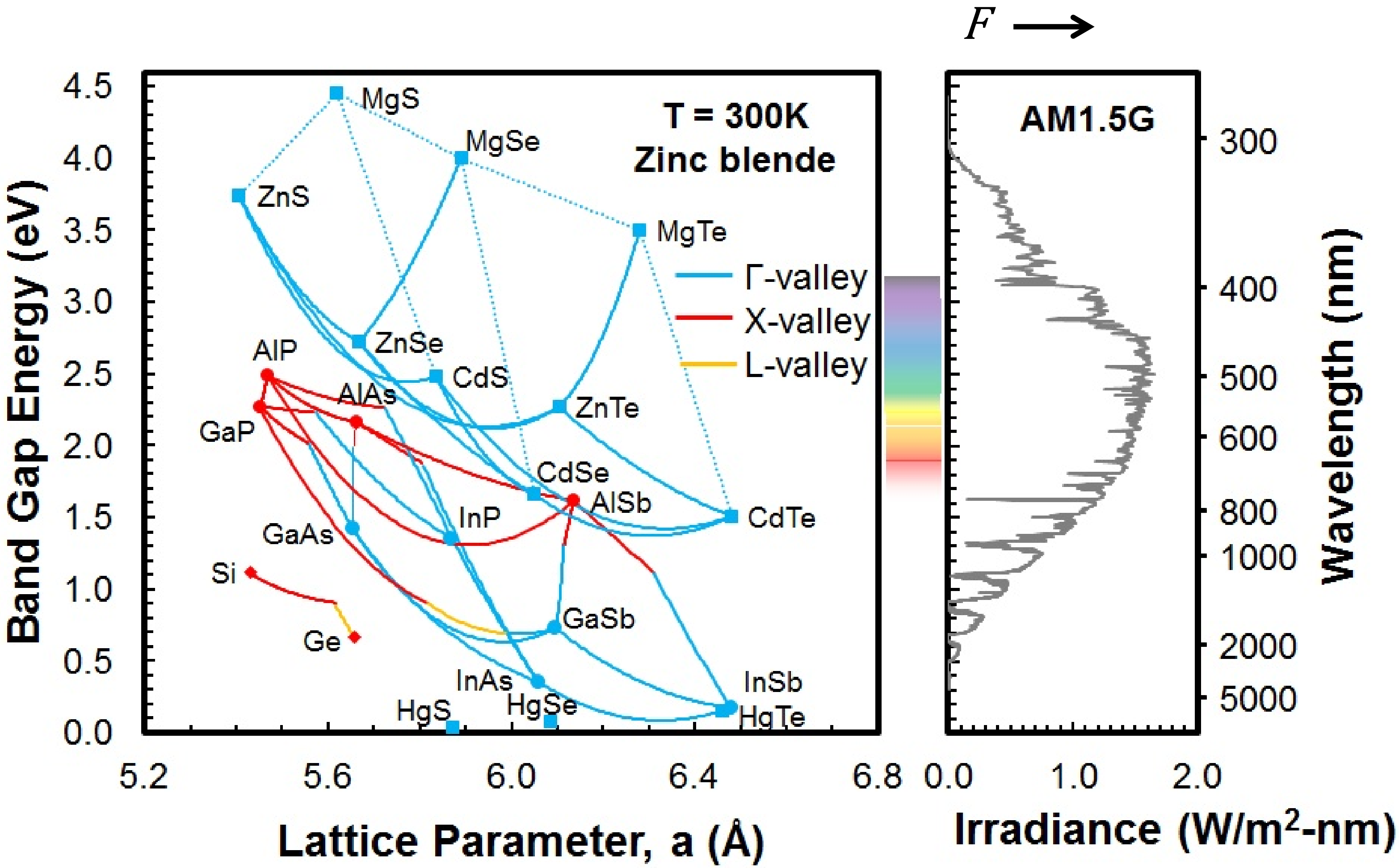
So called „Internal photo effect“



Photons with $\hbar\omega > E_g$ create electron-hole pairs with energy E_g

http://www.pveducation.org/

Band gaps and solar spectra



თეიმურაზ მჭედლიძე

http://woodall.ece.ucdavis.edu/resources.html

Looking for optimal bandgap

All photons are absorbed, no reflection, out of atmosphere…

Efficiency: $\eta_0 = \frac{H_{el}}{H_0}$

H_{el}: electrical power density (W/m^2)

H_o: solar constant

$$H_0 = \frac{R_{sun}^2}{D^2} H_{sun} = \rho^2 \sigma \cdot T_S^4$$

Stefan-Boltzman, $\rho = R_{sun}/D$

$$H_{el} = \rho^2 \cdot \int_{\upsilon=0}^{\infty} F(\upsilon) d\upsilon$$

$$F(\upsilon, T_S) d\upsilon = \Phi(\upsilon, T_S) \cdot h\upsilon d\upsilon$$

F: spectral irradiance

Φ : photonflux

$$H_{el} = \rho^2 \cdot \int_{\upsilon=0}^{\infty} \Phi \cdot h\upsilon d\upsilon$$

For each absorbed photon with $h\upsilon \geq E_g$ an electron-hole pair with energy $h\upsilon_g$ *is created*

$$H_{el} = \rho^2 \cdot h\upsilon_g \int_{\upsilon_g}^{\infty} \Phi(\upsilon, T_S) d\upsilon$$

Looking for optimal bandgap

Spectral irradiance of a blackbody $$F(\lambda,T) = \frac{2\pi h c^2}{\lambda^5\left(exp\left(\frac{E}{kT}\right)-1\right)}$$

[Planck, Annalen der Physik 4, 553-563 (1901)]

$$\lambda = \frac{c}{\upsilon};\ \ d\lambda = -\frac{cd\upsilon}{\upsilon^2} = -\frac{\lambda^2 d\upsilon}{c};\ \ F(\lambda,T)d\lambda = \frac{2\pi h\upsilon^2}{\left(\frac{c}{\upsilon}\right)^3\left(exp\left(\frac{E}{kT}\right)-1\right)}\frac{cd\upsilon}{\upsilon^2} = \frac{2\pi h\upsilon^3}{c^2\left(exp\left(\frac{E}{kT}\right)-1\right)}\ d\upsilon;$$

$$\Phi(\upsilon,T_S)d\upsilon = \frac{2\pi h\upsilon^3}{h\upsilon\ \ c^2\left(exp\left(\frac{E}{kT}\right)-1\right)}d\upsilon = \frac{2\pi\upsilon^2}{c^2\left(exp\left(\frac{h\upsilon}{kT_S}\right)-1\right)}d\upsilon$$

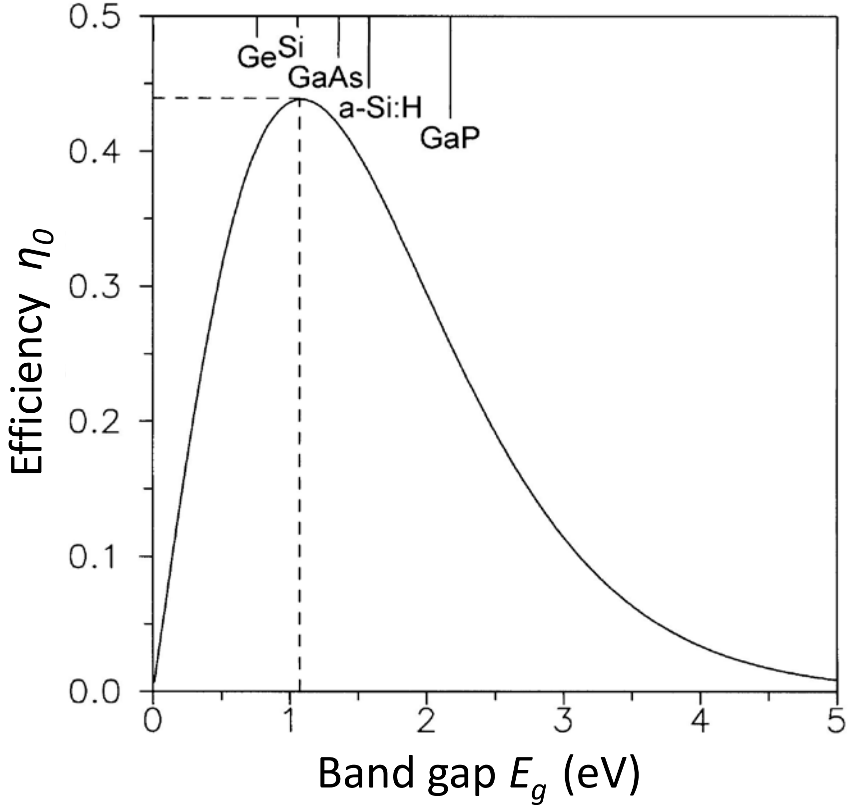
$$\eta_0 = \frac{H_{el}}{H_0} = \frac{h\upsilon_g}{\sigma\cdot T_S^4}\int_{\upsilon_g}^{\infty}\Phi(\upsilon,T_S)d\upsilon = \frac{h\upsilon_g}{\sigma\cdot T_S^4}\int_{\upsilon_g}^{\infty}\frac{2\pi\upsilon^2}{c^2\left(exp\left(\frac{h\upsilon}{kT_S}\right)-1\right)}d\upsilon = \frac{h\upsilon_g}{\sigma\cdot T_S^4}\frac{2\pi}{c^2}\int_{\upsilon_g}^{\infty}\frac{\upsilon^2}{\left(exp\left(\frac{h\upsilon}{kT_S}\right)-1\right)}d\upsilon$$

$$\eta_0 = \frac{h\upsilon_g}{\sigma\cdot T_S^4}\frac{2\pi}{c^2}\cdot I$$ Integral I can be calculated analytically (see [1])

$$I = \upsilon_g^3\cdot\frac{1}{x^4}G(x) \qquad x = \frac{h\upsilon_g}{kT_S} \qquad G(x) = \frac{x^3}{e^x-\frac{1}{2}} + \frac{2x^2}{e^x-\frac{1}{4}} + \frac{2x}{e^x-\frac{1}{8}}$$

 [1] H.-G. Wagemann, H. Eschrich: http://link.springer.com/book/10.1007/978-3-8348-9376-5/page/1

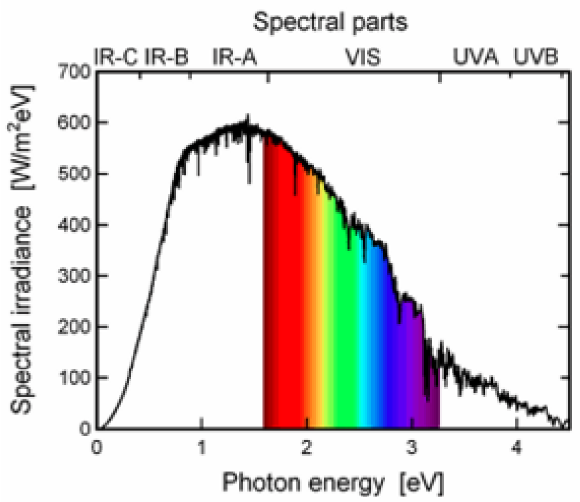
Looking for optimal bandgap



$$\eta_0 = \frac{15}{\pi^4} \cdot G(x)$$

! Ultimate efficiency η_0 !

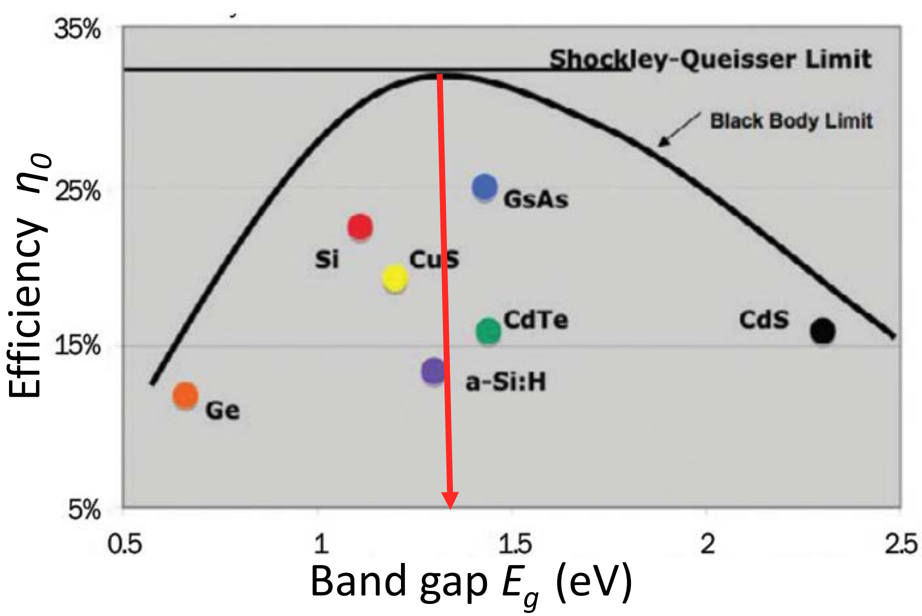
The only criteria is the band gap of the semiconductor.



The Shockley-Queisser efficiency limit

The Critical SQ Limit Assumptions:

- One semiconductor material (excluding dopants) per solar cell;
- One p/n junction per solar cell;
- The sunlight is not concentrated - a "one sun" source;
- All energy is converted to heat from photons greater than the band gap.



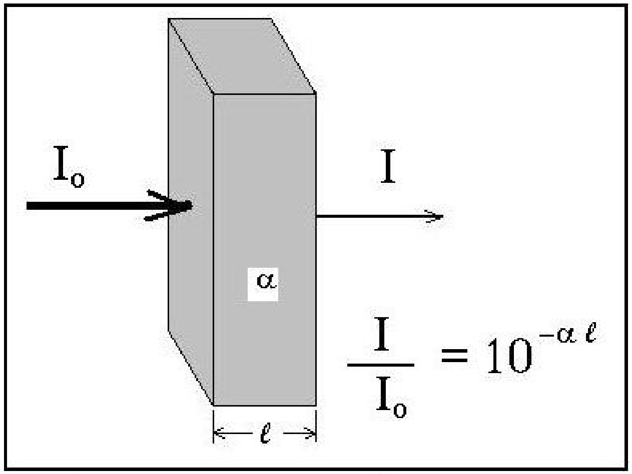
Where Does The 67% Of Energy Loss Go?

- 47% of the solar energy gets converted to heat.
- 18% of the photons pass through the solar cell.
- 0.2% of energy is lost from local recombination of newly created holes and electrons.

According to the SQ model the optimal band-gap for the solar spectra is 1.4 eV

W. Shockley and H. J. Queisser, Journal of Applied Physics, **32** (1961) 510
http://solarcellcentral.com/limits_page.html

Light absorption, Lambert-Beer's law



Spectral photon flux: $\Phi(\lambda) = \frac{F(\lambda)}{hc}\lambda$

In homogeneous semiconductor $\Phi(\lambda)$ will be reduced proportional to its value and thickness:

$$-\frac{\partial\Phi(\lambda, x)}{\partial x} = \alpha(x)\Phi(\lambda, x)$$

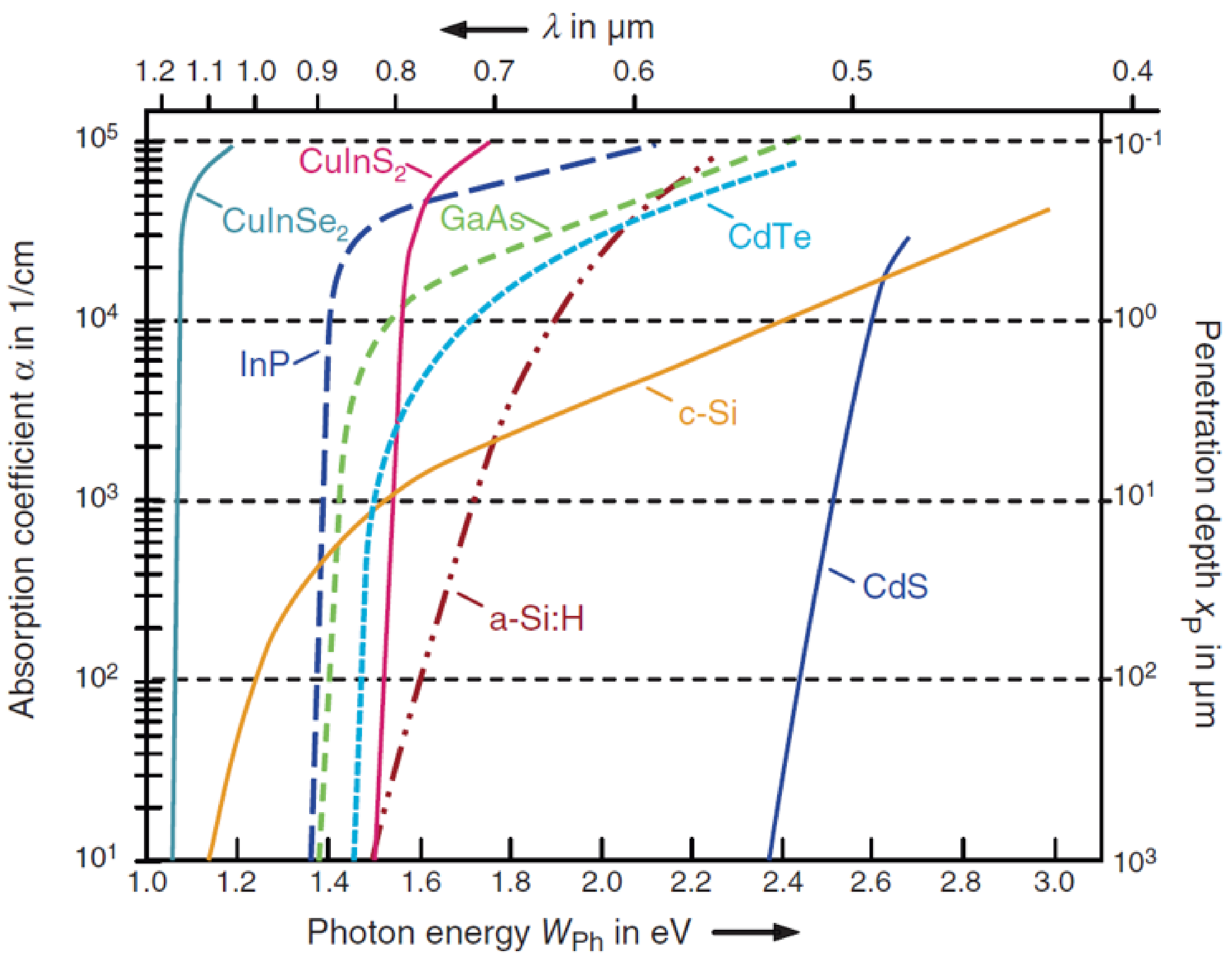
$$\Phi(\lambda, x) = \Phi(\lambda, x = 0)e^{-\alpha(\lambda)x}$$

By absorption of photons, electron-hole pairs are generated.

Generation rate: $G(\lambda, x) = -\frac{\partial\Phi(\lambda,x)}{\partial x}$ where G(N/s m^3), N number of electrons.

$$G(\lambda, x) = \alpha(x)\Phi(\lambda, x = 0)e^{-\alpha(\lambda)x}$$

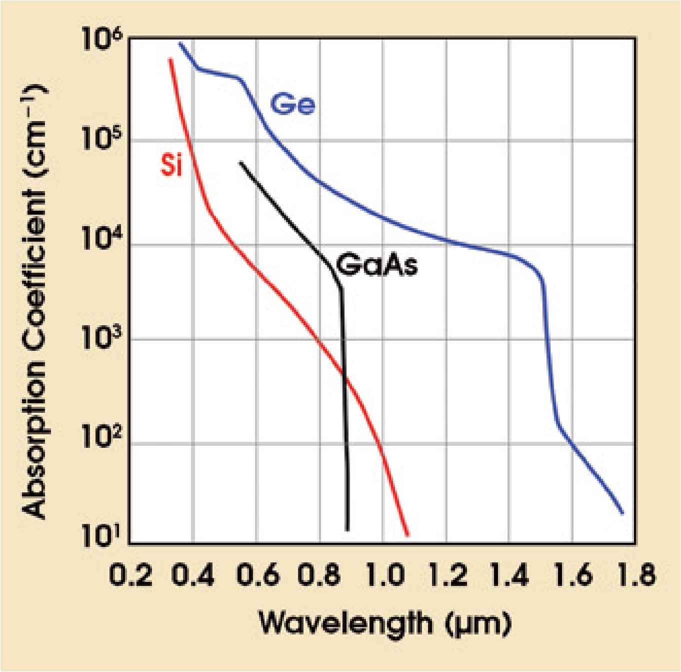
Absorption coefficients in semiconductors

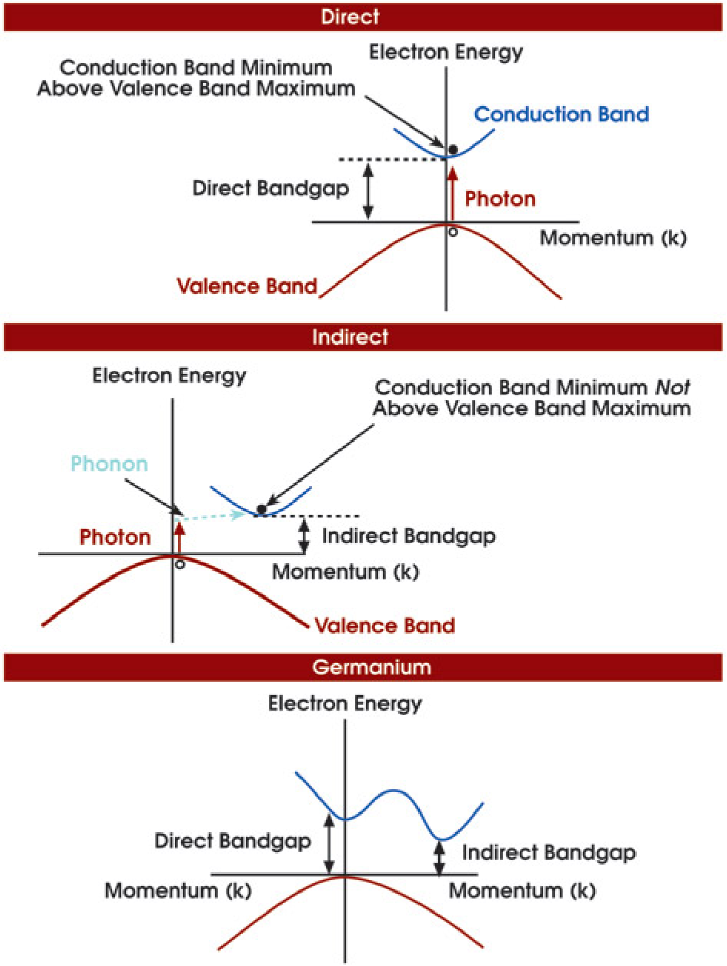


Source: K. Mertens: textbook-pv.org

The absorption (penetration) depth is the inverse of the absorption coefficient. An absorption depth of, for example, 1 μm means that the light intensity has fallen to 36% (1/e) of its original value.

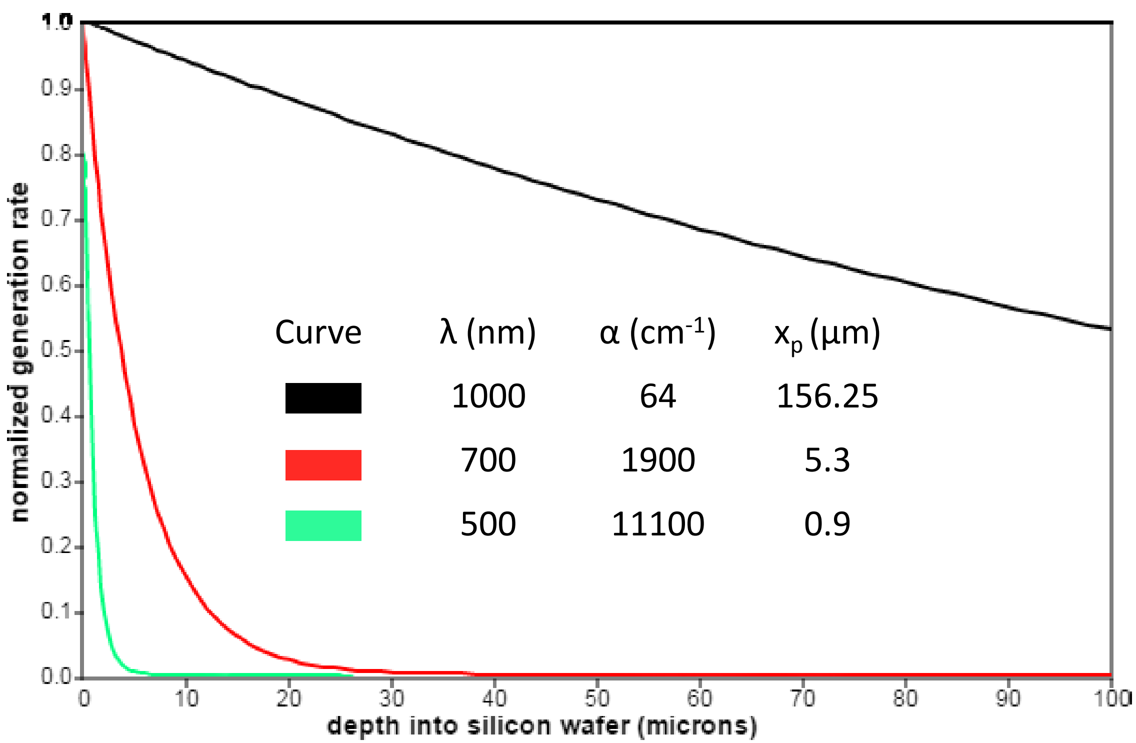
Absorption coefficients in semiconductors





http://www.photonics.com/

Generation rate for various wavelengths



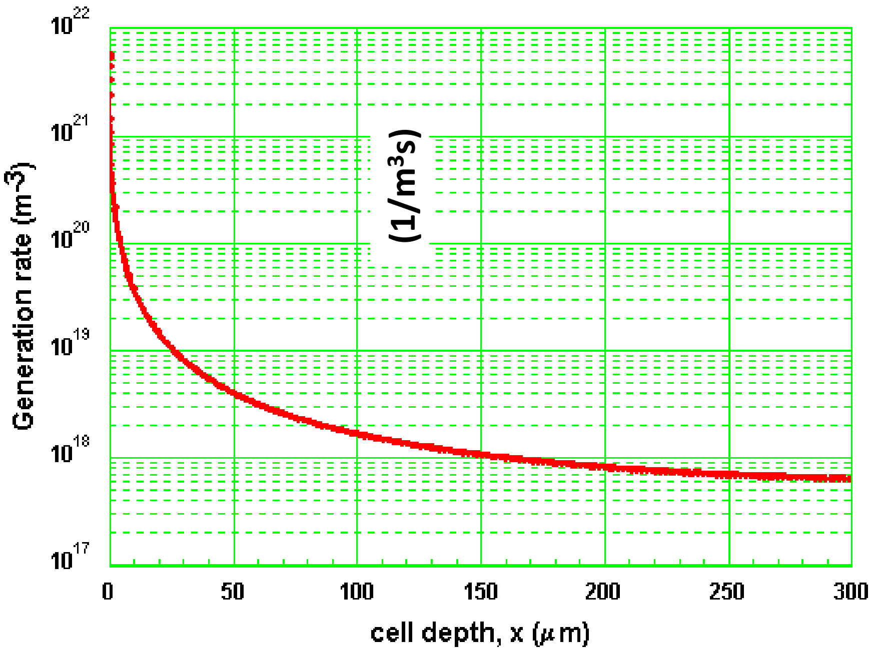
Silicon, 300 K

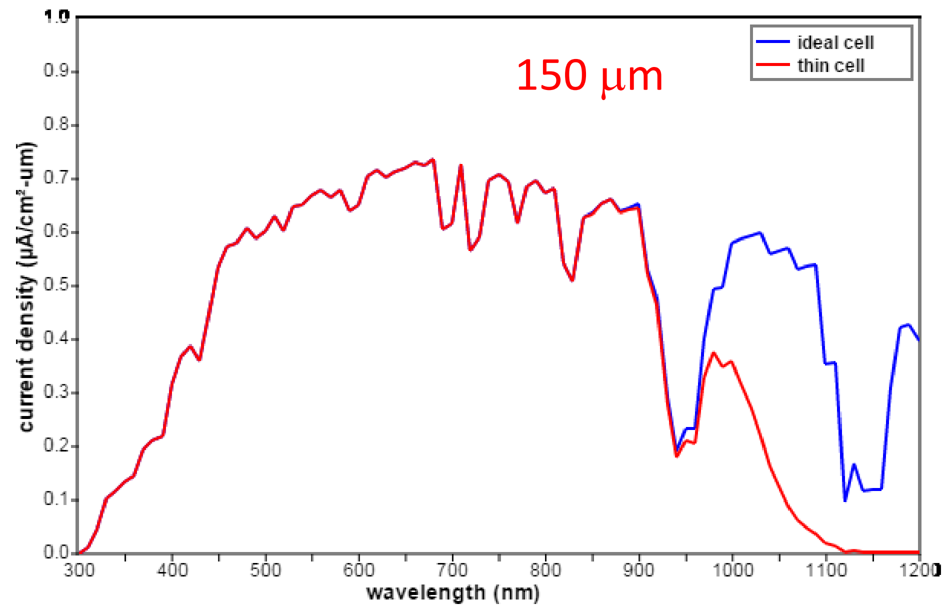
http://www.pveducation.org/pvcdrom/pn-junction/generation-rate

Generation rate for solar spectrum

$$G(x)=\int_0^{\lambda_g} G(\lambda,x)d\lambda \quad \text{with} \quad \lambda_g=\frac{hc}{E_g}$$

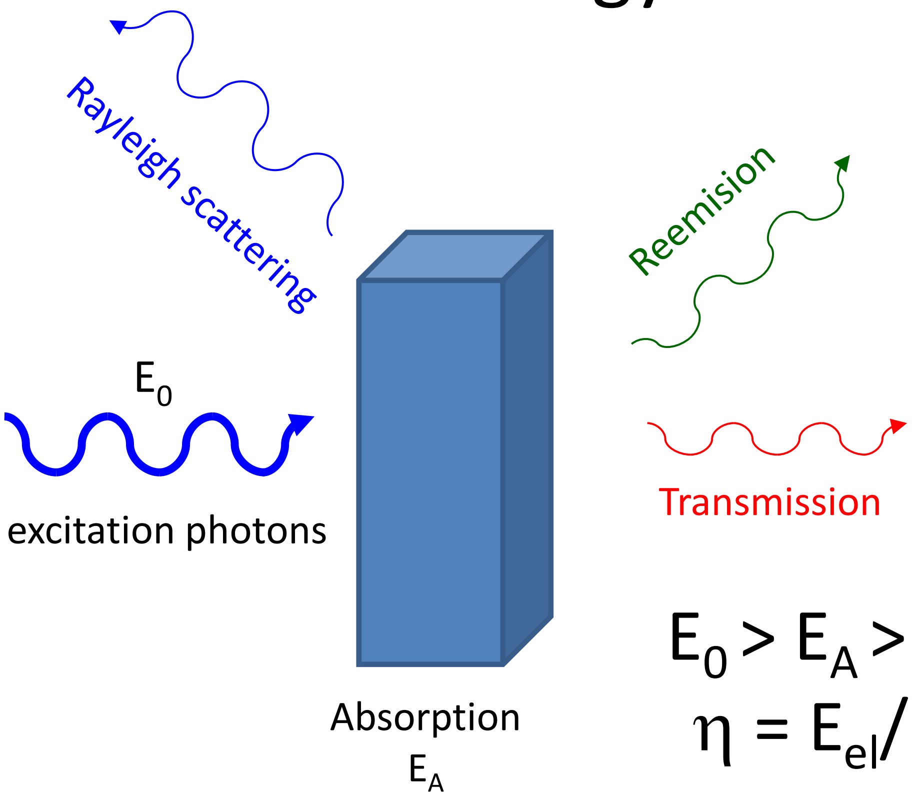
For a standard solar spectrum (AM 1.5) incident on silicon:





Generation rate of electron-hole pairs in a piece of silicon as a function of distance into the cell. The cell front surface is at 0 µm and most of the high energy photons are absorbed very close to it.

Energy losses - efficiecy



- **Transmission**: E_g too large
- **Scattering**: Surface and photon – phonon interactions
- **Reemission:** non-separation and defects
- **Thermalisation:** E_g too small

$$E_0 > E_A > E_{el}$$

$$\eta = E_{el}/E_0$$

Solar flux → Absorption → Excitation → Charge separation → Charge drift → Charge collection

$$\eta_{TOTAL} = \eta_{ABSORPTION} \times \eta_{EXCITATION} \times \eta_{SEPARATION} \times \eta_{DRIFT} \times \eta_{COLLECTION}$$

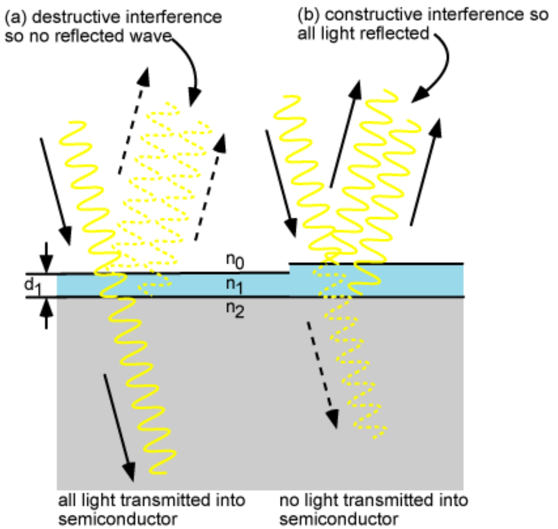
თეიმურაზ მჭედლიძე

Suppress losses – increase efficiency

$$\eta_{TOTAL}=\eta_{ABSORPTION}\times\eta_{EXCITATION}\times\eta_{SEPARATION}\times\eta_{DRIFT}\times\eta_{COLLECTION}$$

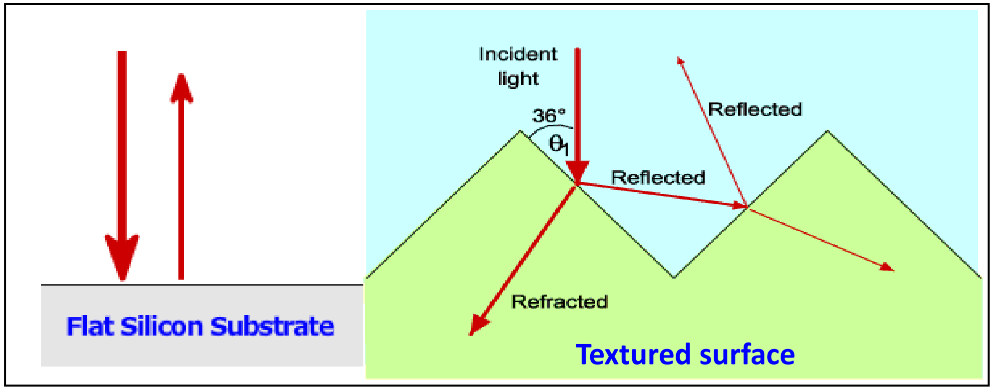
For minimizing absorption losses: "Light management methods"

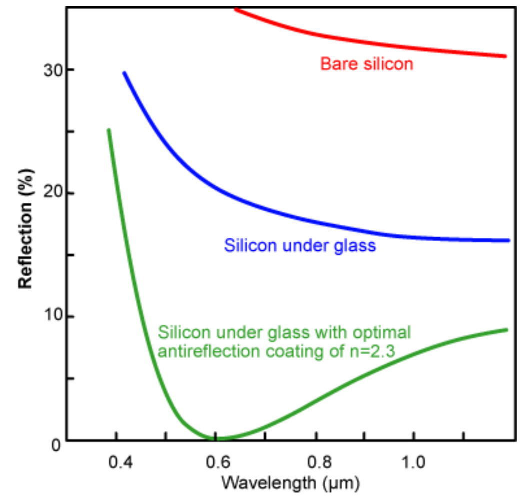
- Anti-reflection coating;
- Surface texturization;
- Back surface reflection, "light trapping";
- Etc.



$d_1=\lambda_0/4n_1$ (e.g. for $n_1=2$ and $\lambda_0=560$ nm, $d_1=70$ nm)

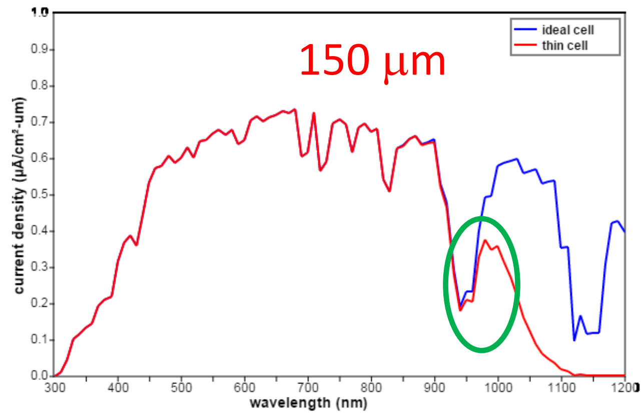
$n_1=(n_0\times n_2)^{1/2}$ (n_2(Si, 560 μm)≈4, n_0(air)=1)

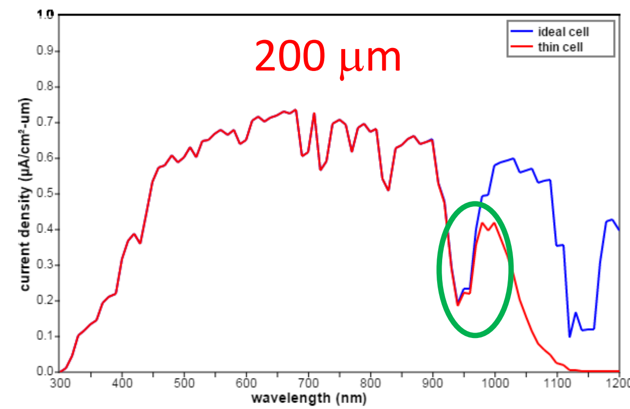




Suppress losses – increase efficiency

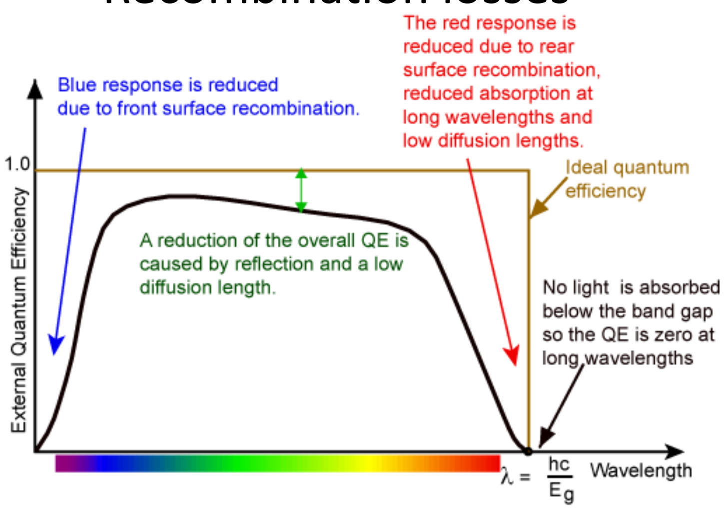
$$\eta_{TOTAL}=\eta_{ABSORPTION}\times\eta_{EXCITATION}\times\eta_{SEPARATION}\times\eta_{DRIFT}\times\eta_{COLLECTION}$$

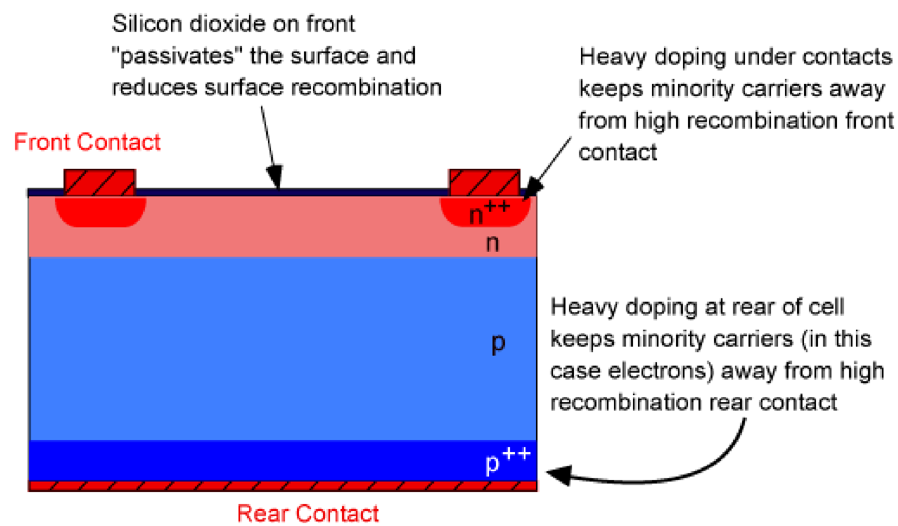




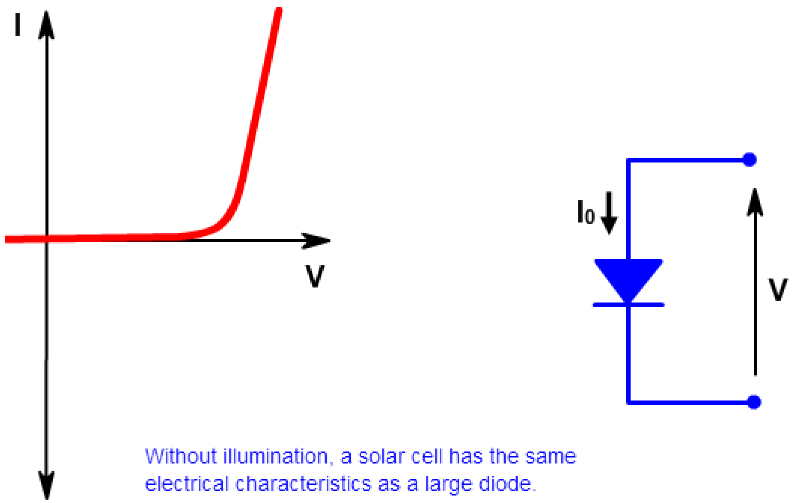
$$\eta_{TOTAL}=\eta_{ABSORPTION}\times\eta_{EXCITATION}\times\eta_{SEPARATION}\times\eta_{DRIFT}\times\eta_{COLLECTION}$$

“Recombination losses”



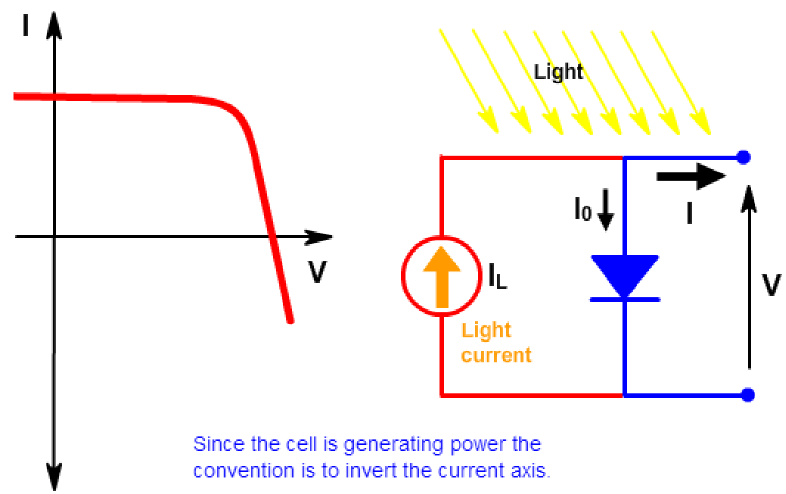


IV curve for a solar cell



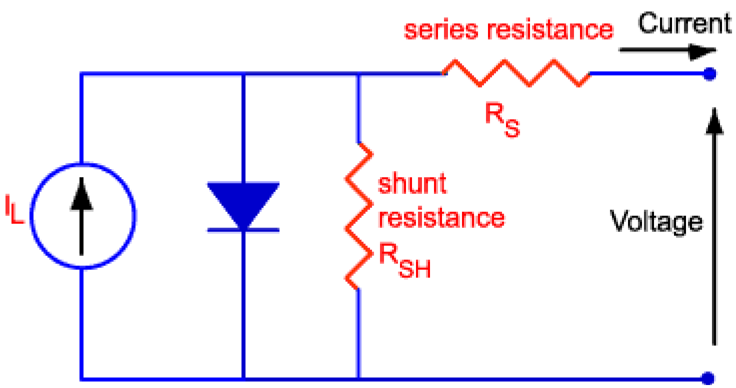
$$I = I_0[\exp(qV/nkT) - 1]$$

$$I = I_L - I_0[\exp(qV/nkT) - 1]$$

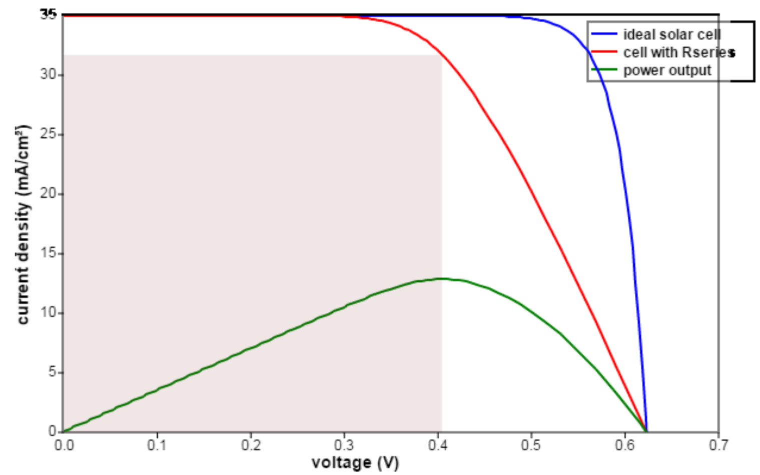


Suppress losses – increase efficiency

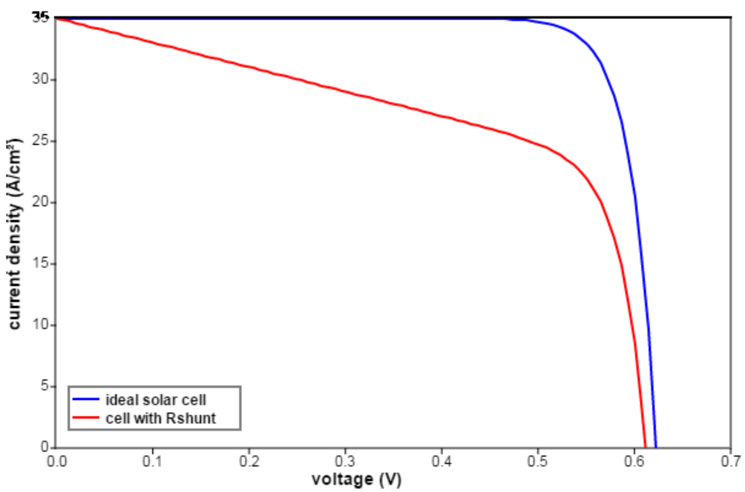
$$\eta_{TOTAL}=\eta_{ABSORPTION}\times\eta_{EXCITATION}\times\eta_{SEPARATION}\times\eta_{DRIFT}\times\eta_{COLLECTION}$$



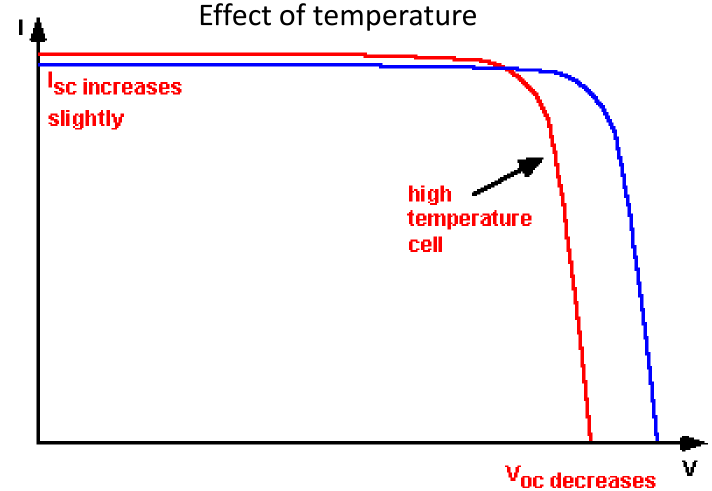
Cell series resistance 5 Ωcm^2



Cell shunt resistance 50 Ωcm^2

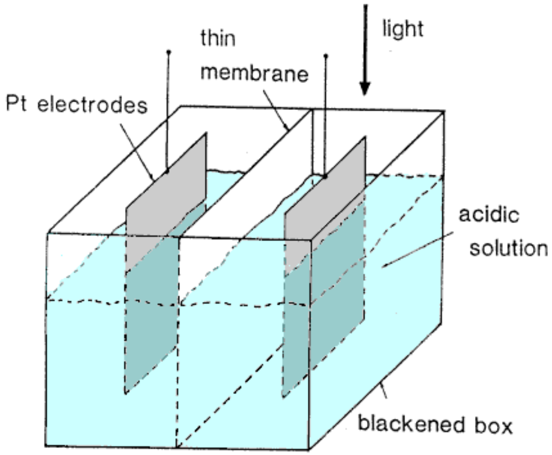


Effect of temperature

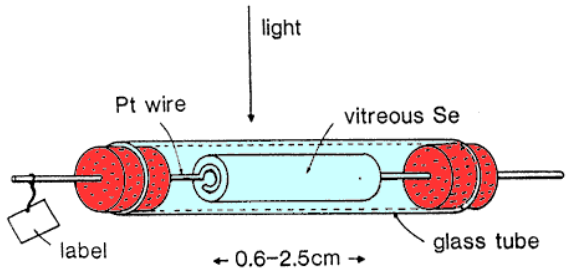


http://www.pveducation.org/

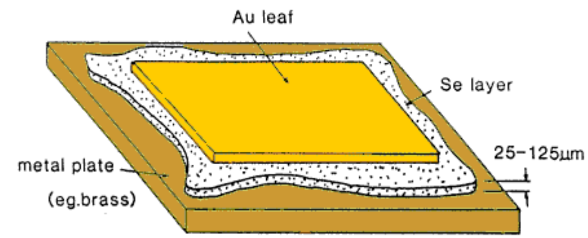
The history of photovoltaic devices



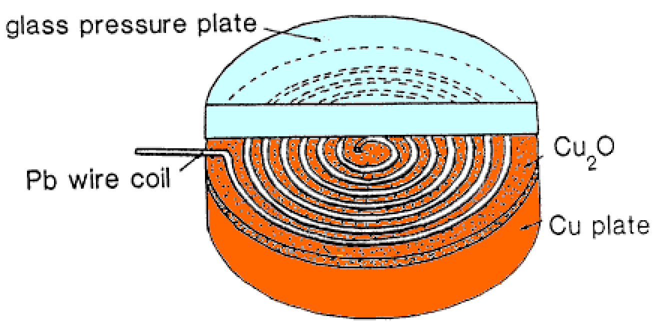
Edmond Becquerel (1839)

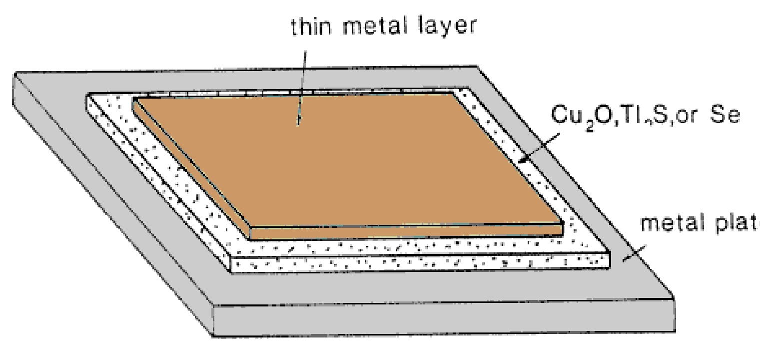


Adams and Day (1876)



Fritts (1883)



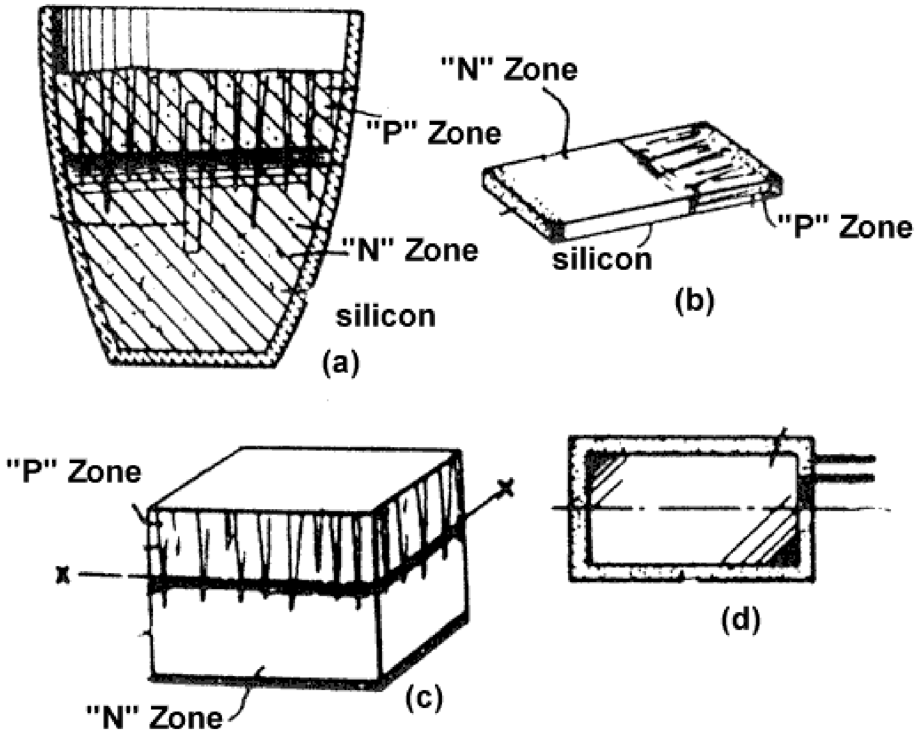


Grondahl, Geiger, Bergmann, Nix… (circa ~1927-40).

http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=111582

First silicon cells

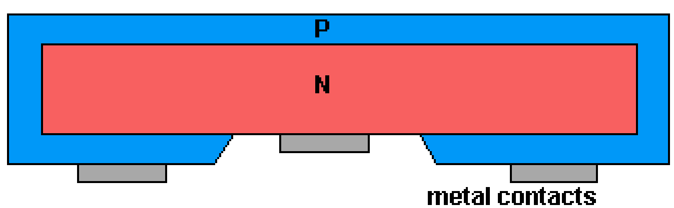
Ohl RS. Light-Sensitive Electric Device. U.S. Patent. 1941; 2:402, 602.



“Natural Si junctions”

η<0.4%

Chapin, Fuller and Pearson (1954)



η=6%

Si cell efficiency progress

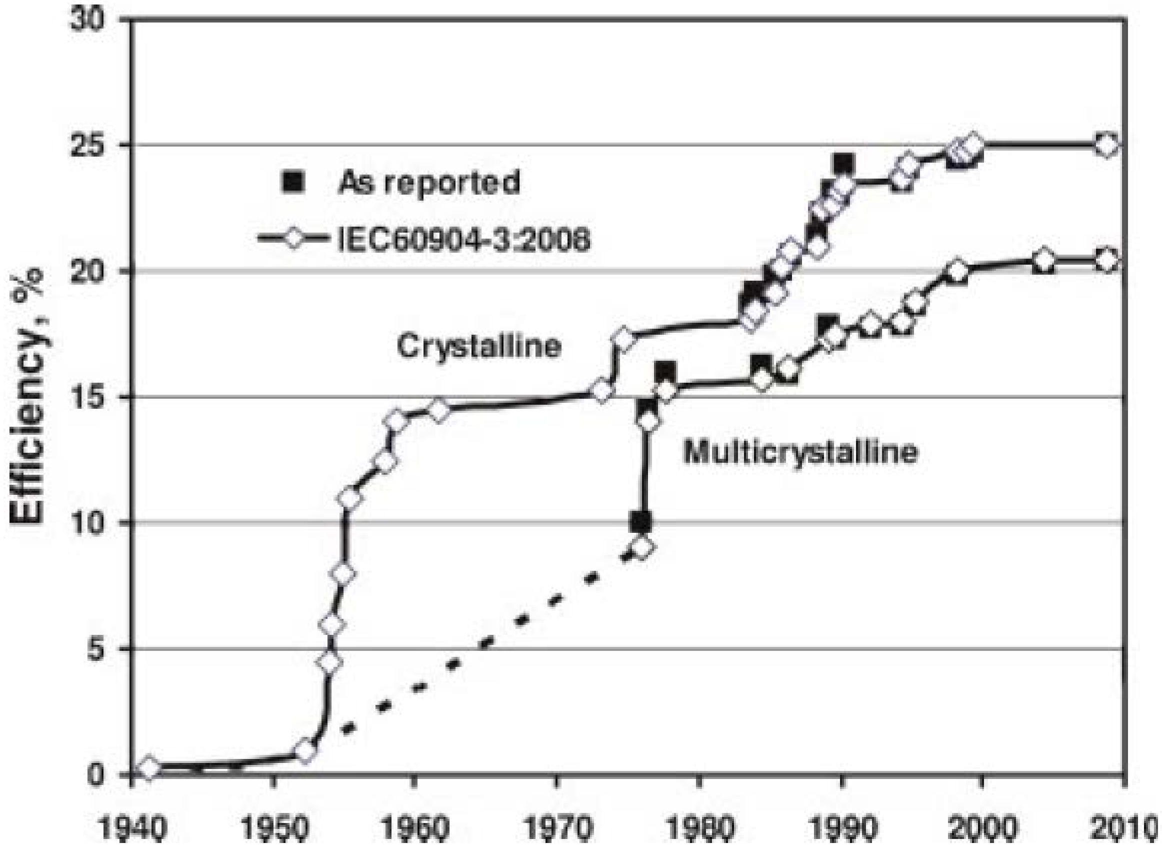


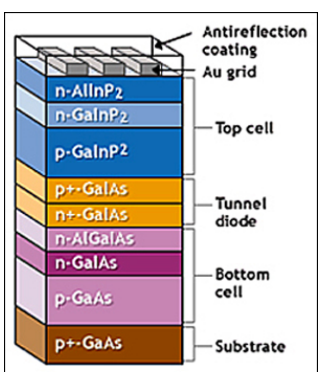
Figure 3. Evolution of crystalline and multicrystalline silicon solar cell efficiency

M.A. Green, Prog. Photovolt: Res. Appl. 17,183 (2009)

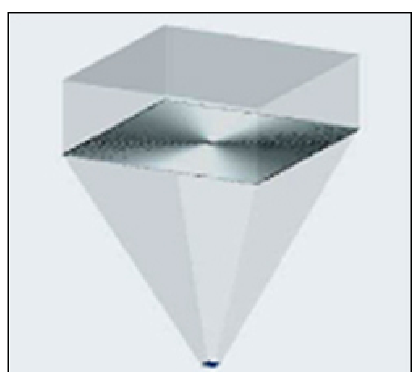
Strategies to exceed the SQ limit

	SQ limit assumptions	A strategy to overcome
1	One semiconductor material (excluding doping materials) per solar cell	Use more than one semiconductor material in a cell
2	One P/N junction per solar cell	Use more than one junction in a cell - "tandem cells"
3	The sunlight is not concentrated - a "one sun" source	Sunlight can be concentrated about 500 times using inexpensive lenses
4	All energy is converted to heat from photons greater than the band gap	Combine a PV semiconductor with a heat based technology; Use "quantum dots" to harvest some of the excess photon energy for electricity

1,2



3



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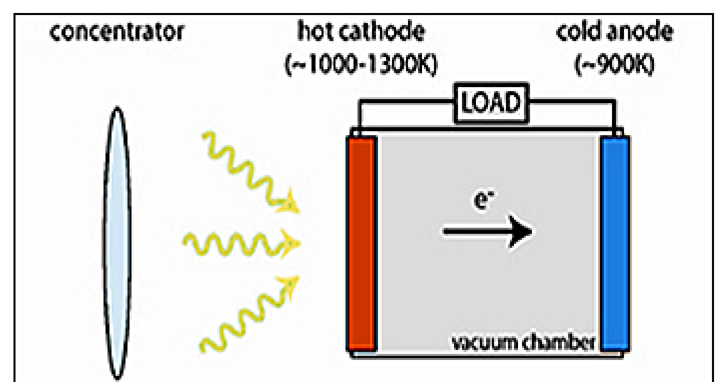


თეიმურაზ მჭედლიძე

http://solarcellcentral.com/limits_page.html

დასკვნები

- ნივთიერებაზე დაცემული სინათლის მხოლოდ ნაწილი შთაინთქმება დანარჩენი აირეკლება, გარდაიქმნება სხვა სახის გამოსხივებად ან გატარდება შეუცვლელად.
- შთანთქმული სინათლის ელექტრობად გადასაქცევად საჭიროა ნივთიერების ისეთი სტრუქტურა სადაც ელექტრონები სინათლესთან ურთიერქმედების შედეგად თავისუფლები ხდებიან და შეუძლიათ ნივთიერებაში გადაადგილება ელექტრული ველის ზეგავლენით (ნახევარგამტარები).
- თუ მარტო მზის სპექტრის შთანთქმის შედეგად თავისუფალი ელექტრონების წარმოქმნას მივიღებთ მხედველობაში, სილიციუმი საუკეთესო ნივთიერებაა ფოტოვოლტაიკისათვის.

დასკვნები

- თეორეტიკული ეფექტურობის ლიმიტი (SQ-limit) ერთი ნივთიერების, ერთი -გადასვლის, არაკონცენტრირებული მზის გამოსხივებისა და სითბური დანაკარგების გათვალისწინებით არის 33.7%. SQ-ლიმიტის გაუმჯობესება შესაძლებელია ერთი ან რამდენიმე ზემოაღნიშნული პირობის შეცვლის გზით.

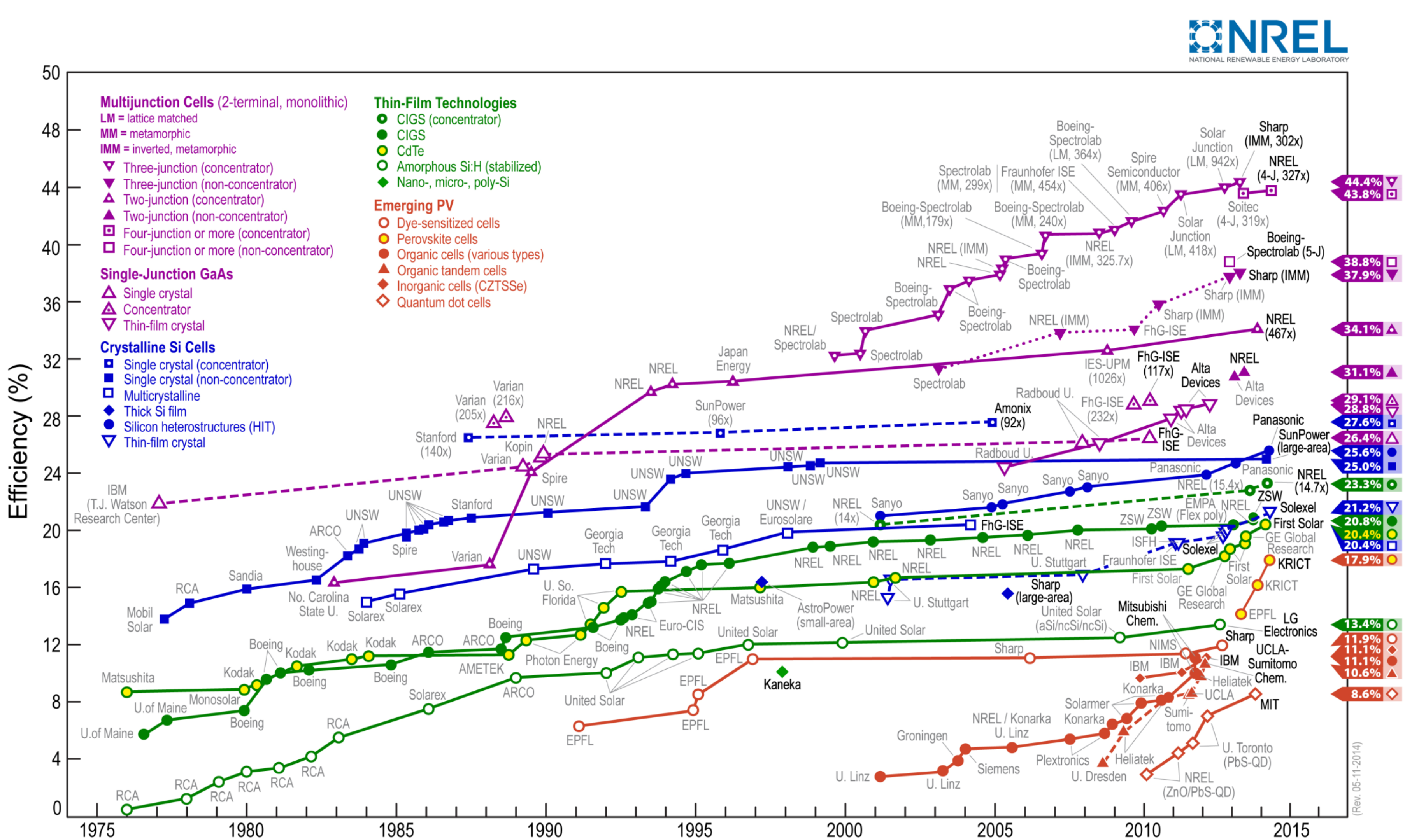
- მაღალი ფოტოვოლტაიკური ეფექტურობის მისაღებად საჭიროა ყველა შესაძლებელი დანაკარგების შემცირება. სინათლის შთანთქმის, დენის მატარებლების გენერაციის, მათი გადაადგილების და შეგროვების დანაკარგების შემცირება წარმოადგენს თანამედროვე კვლევის ერთ-ერთ მთავარ ამოცანას.

- ფოტოვოვტაიკური ელემენტების ეფექტურობა ბოლო 80 წლის განმავლობაში 0.0006%-დან 0.26%-მდე გაიზარდა (600-ჯერ!).

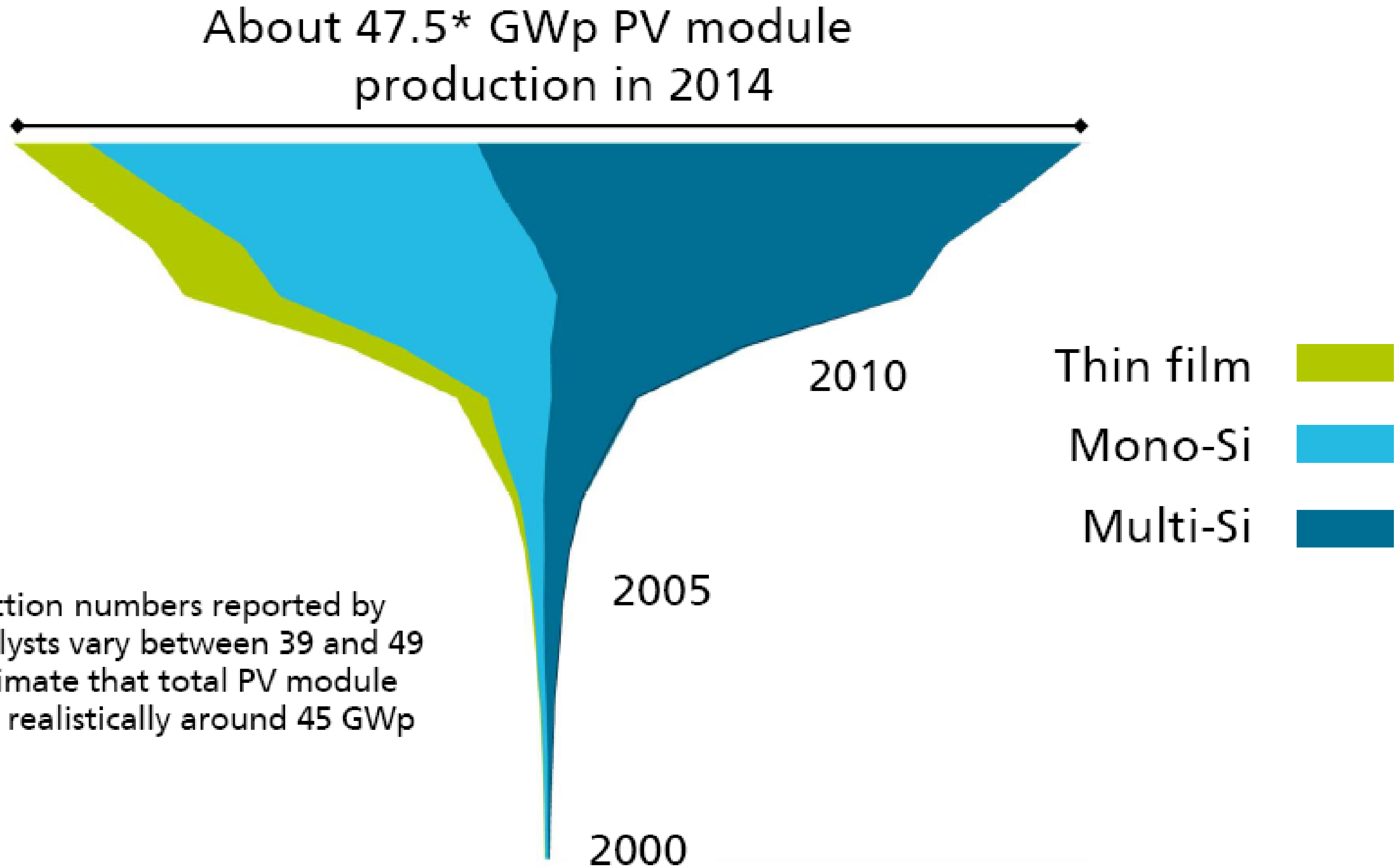
ლექცია III: ფოტოვოლტაიკური ელემენტები მოდულები, ქსელები.

- თანამედროვე ფოტოვოლტაიკური ელემენტები;
- კრისტალური Si ელემენტების წარმოება;
- ფოტოვოლტაიკური მოდულები;
- ქსელების და ელექტრობის აკუმულაციის ალტერნატივა;
- განახლებადი ენერგიის წყაროების შედარება;
- ფოტოვოლტაიკის ეკონომიკა და ფილოსოფია;
- დასკვნები და მომავლის პერსპექტივა.

Progress in research-cell efficiencies



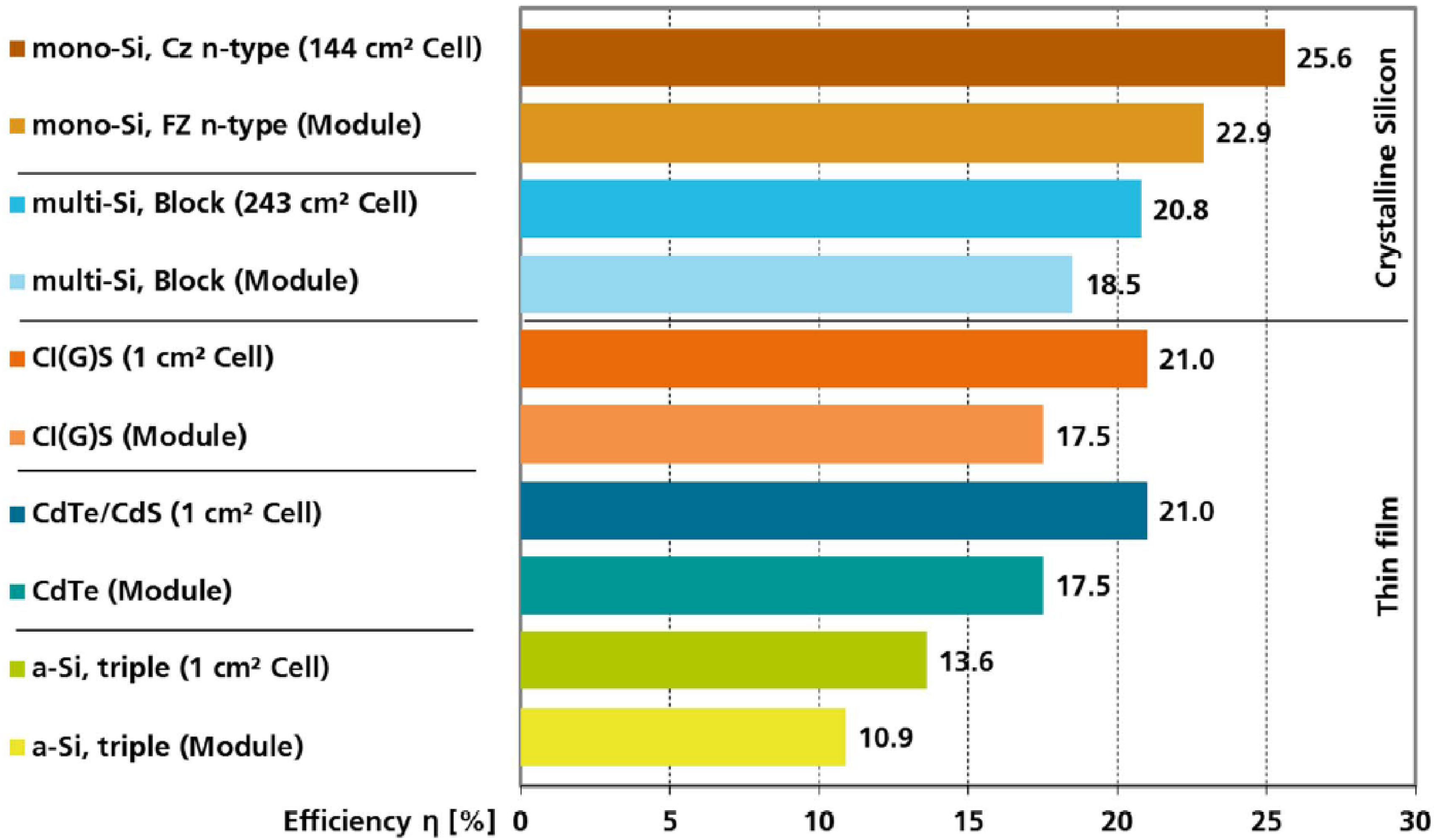
Annual PV Production by Technology Worldwide (in GWp)



*2014 production numbers reported by different analysts vary between 39 and 49 GWp. We estimate that total PV module production is realistically around 45 GWp for 2014.

Data: from 2000 to 2010: Navigant; from 2011: IHS (Mono-/Multi- proportion: Paula Mints). Graph: PSE AG 2015

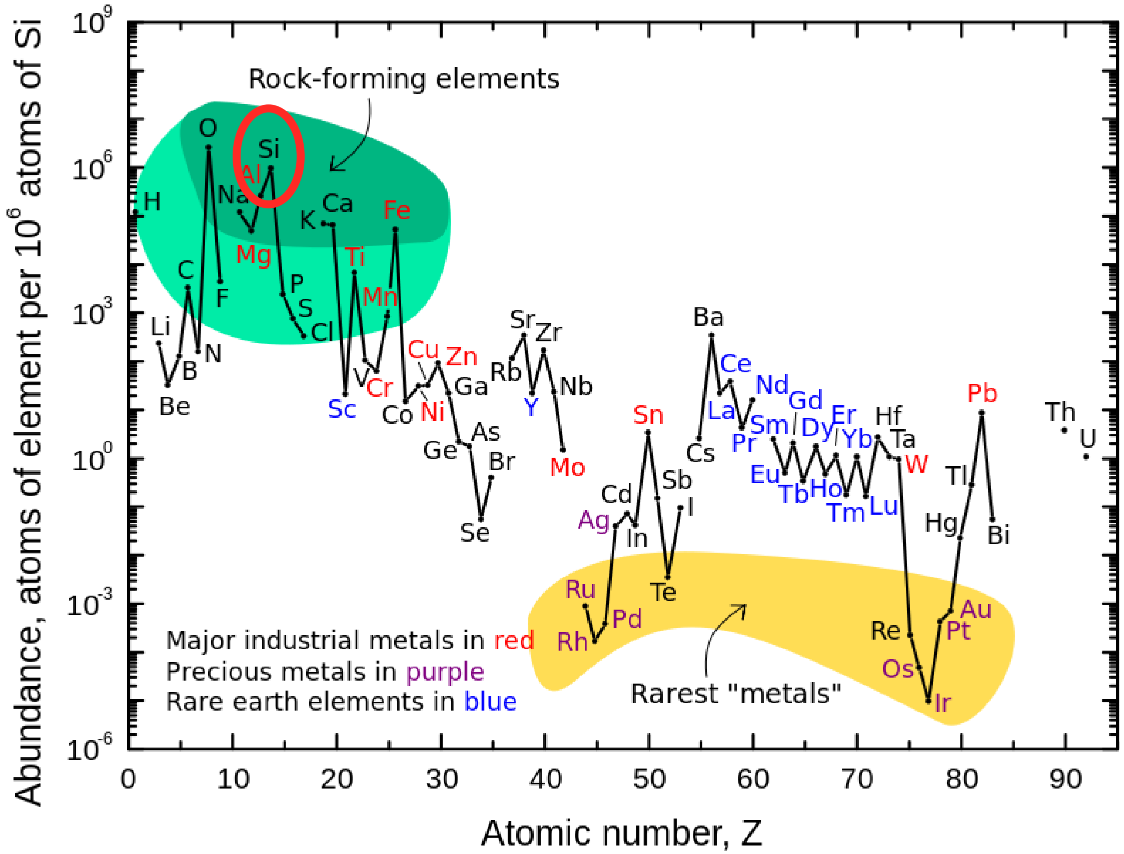
Efficiency Comparison of Technologies: Best Lab Cells vs. Best Lab Modules



თეიმურაზ მჭედლიძე

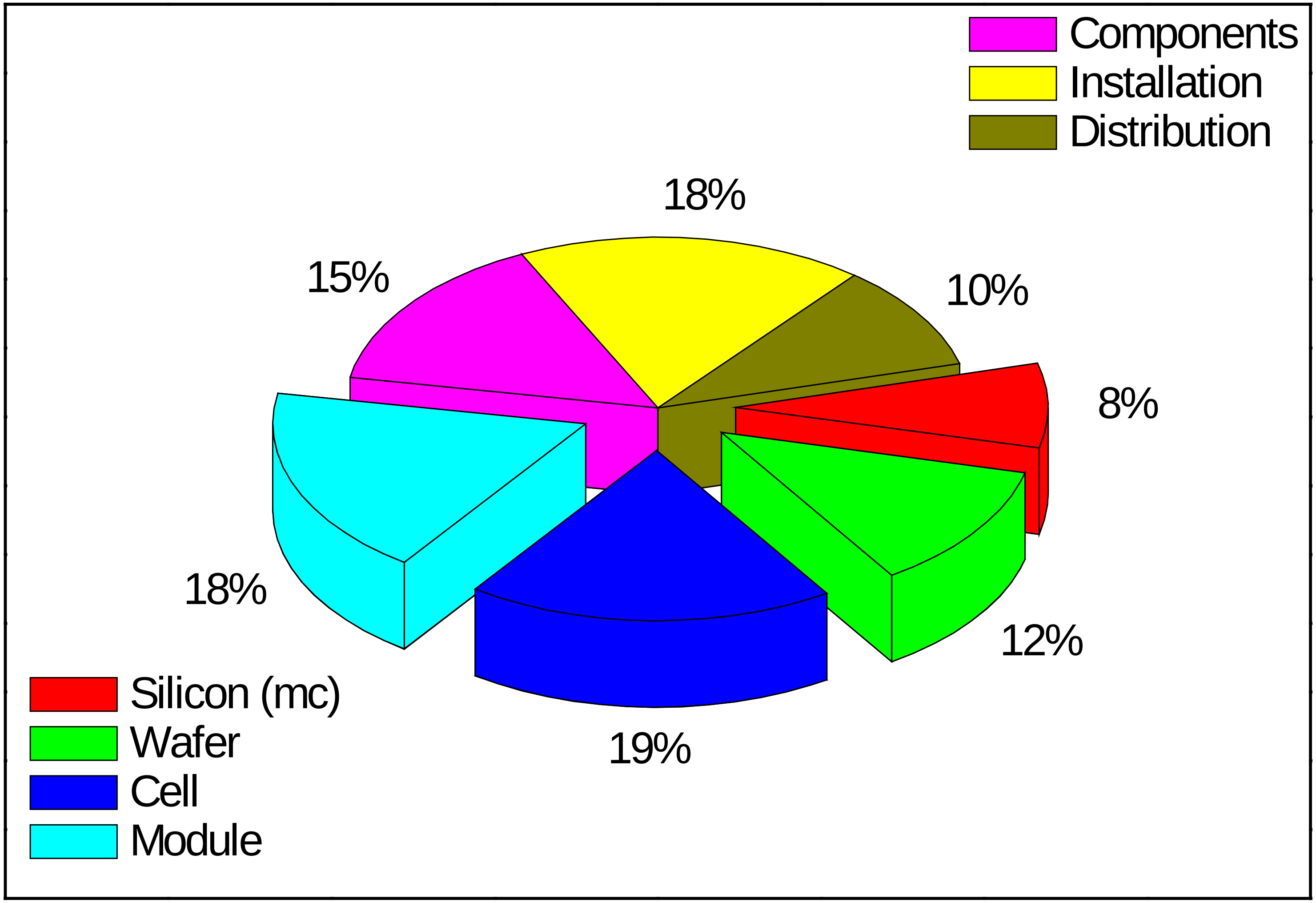
Why Si

- Second most abundant element on the earth after oxygen;
- Non toxic;
- Well developed Si industry and technology;
- Fast forming SiO_2 protective layer on the open Si surface and its passivation properties;
- Suitable value for the bandgap;
- High value of real refraction index;
- Low solubility limits for the most of the elements; Candidate for new mass standard!



http://pubs.usgs.gov/fs/2002/fs087-02/

Cost distribution for PV systems, an estimate



Refining silicon

1. Beach sand, Quartz rock 1500-2000^{o}C, electrode arc furnace

$$SiO_2 + C \rightarrow Si + CO_2$$

MG-Si, 98% pure (B, P, Alkali, earth, transition metals, carbon…)

2. Powdered MG-Si 300^{o}C, fluidized bed reactor

$$Si + 3HCl \rightarrow SiHCl_3 + H_2 \text{ (+FeCl}_3\text{, AlCl}_3\text{, BCl}_3\text{)}$$

The resulting $SiHCl_3$ now has impurities of less than 1 ppba.

3. The pure $SiHCl_3$ is reacted with H at 1100°C for ~200 – 300 hours

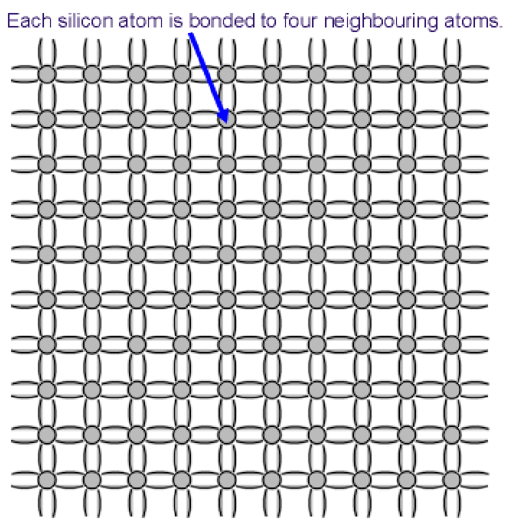
$$SiHCl_3 + H_2 \rightarrow Si + 3\ HCl$$

(Siemens process, ‘60)

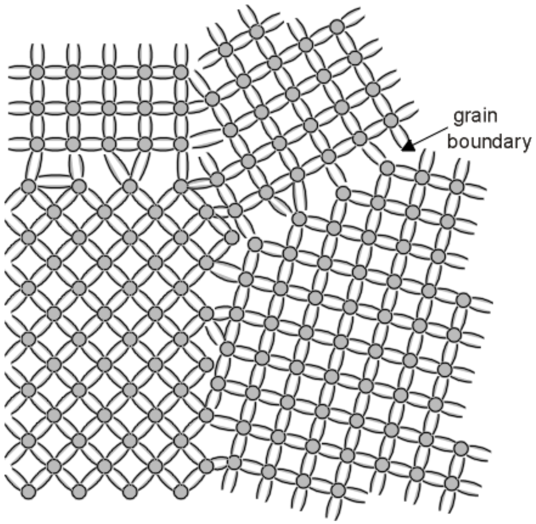
Types of silicon

Descriptor	Symbol	Grain Size	Common Growth Techniques
Single crystal	c-Si	>10cm	Czochralski (Cz) Float zone (FZ)
Multicrystalline	mc-Si	1mm-10cm	Cast, sheet, ribbon
Polycrystalline	pc-Si	1µm-1mm	Chemical-vapour deposition
Microcrystalline	µc-Si	<1µm	Plasma deposition
Amorphous	a-Si	-	Plasma deposition

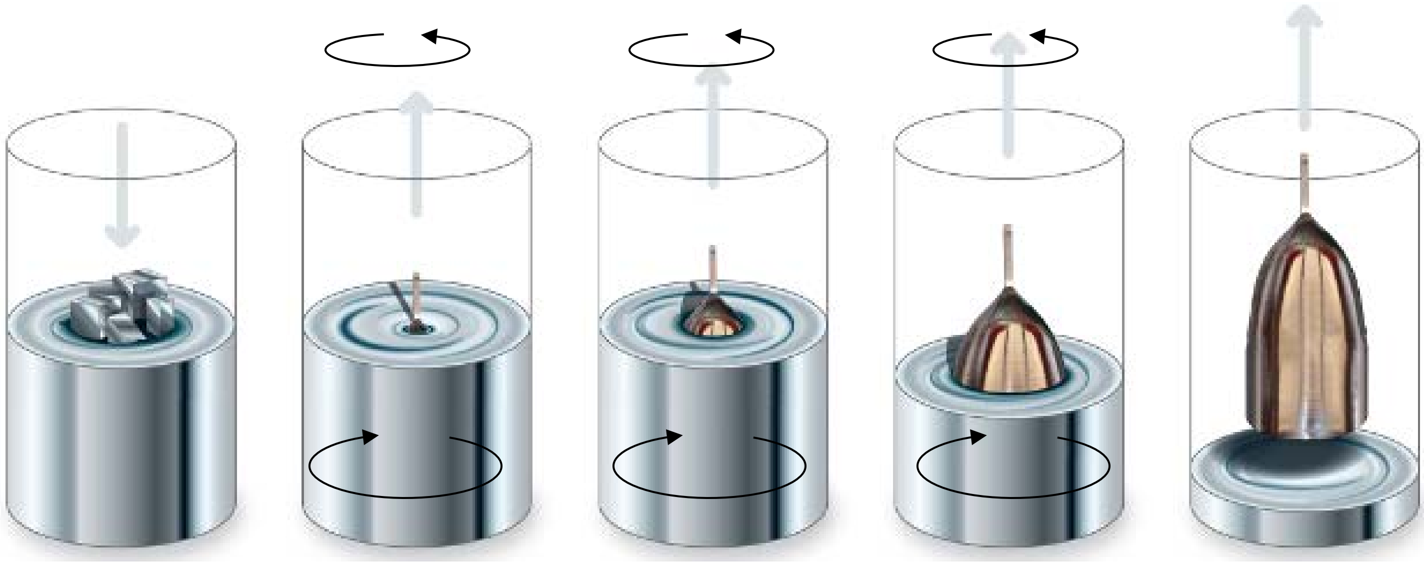
c-Si

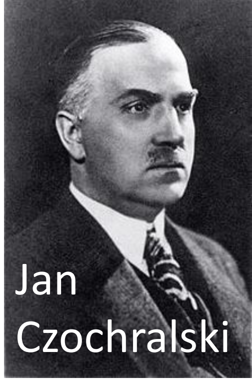


mc-Si



Czochralski growth process





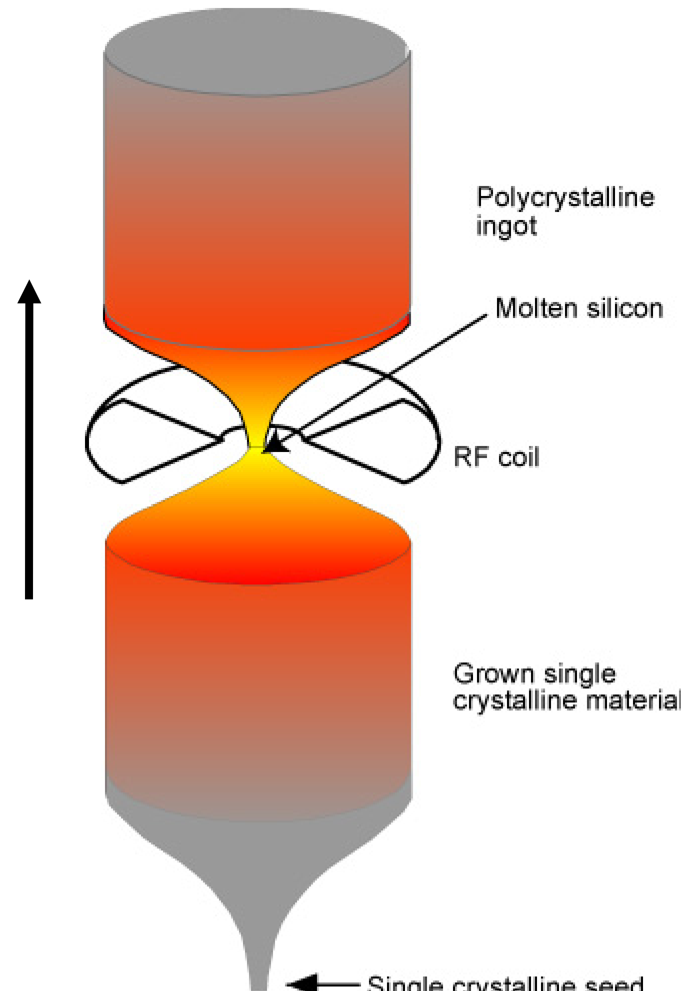
~1916

Poly Si

Diameter up to 45 cm

https://www.th-nuernberg.de

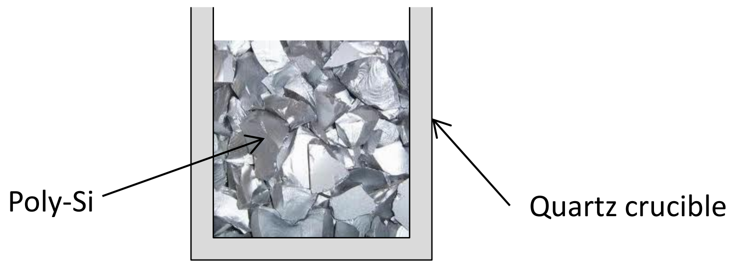
Floating zone growth process



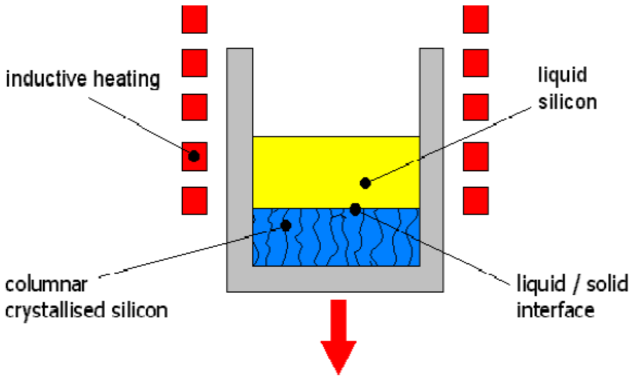
William Gardner Pfann
and Henry Theuerer
Bell Labs, ~1955

Diameter up to 20 cm

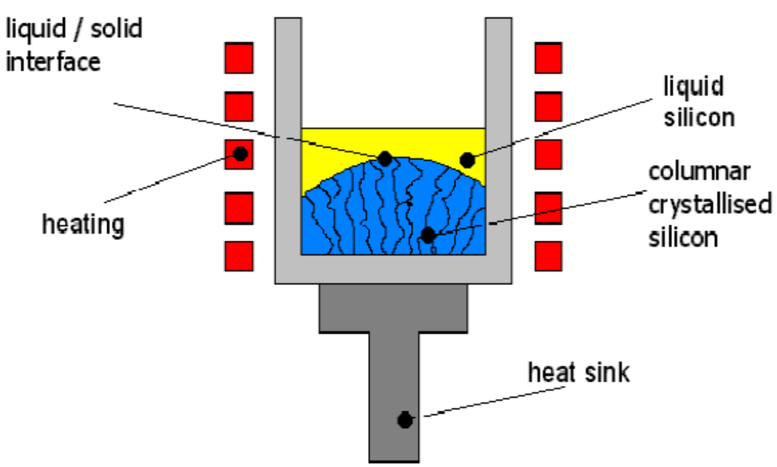
mc-Si fabrication



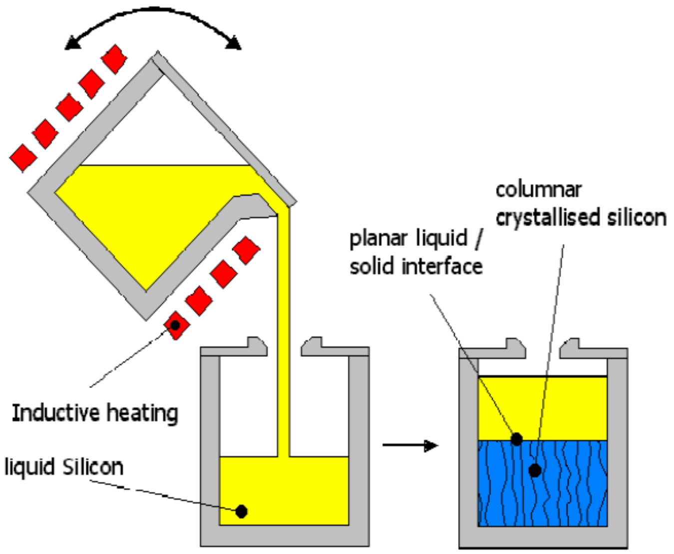
Bridgman solidification



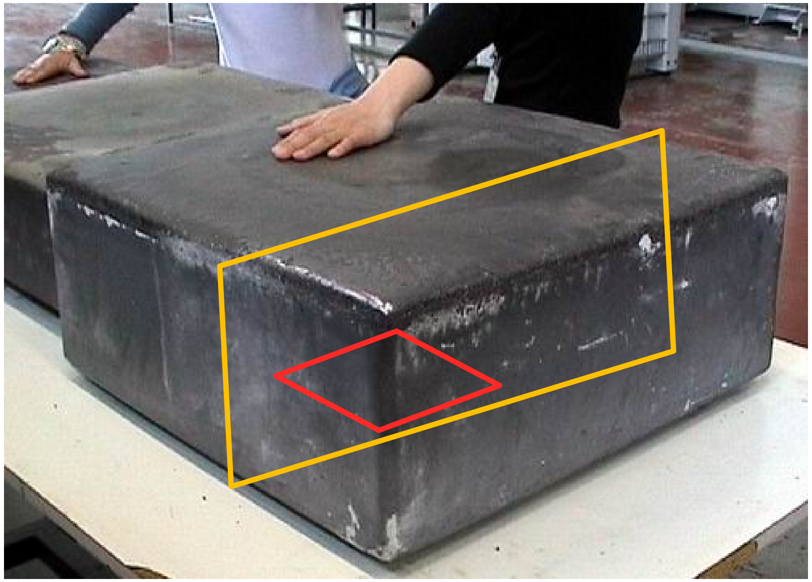
Heat exchange method (HEM)

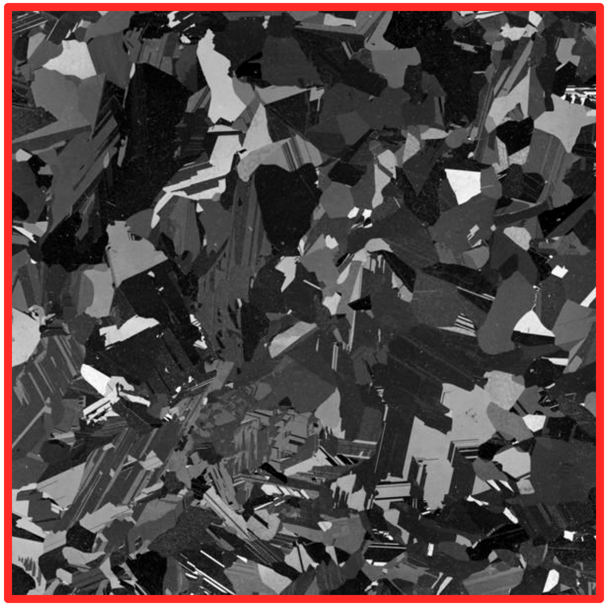


Casting of silicon blocks

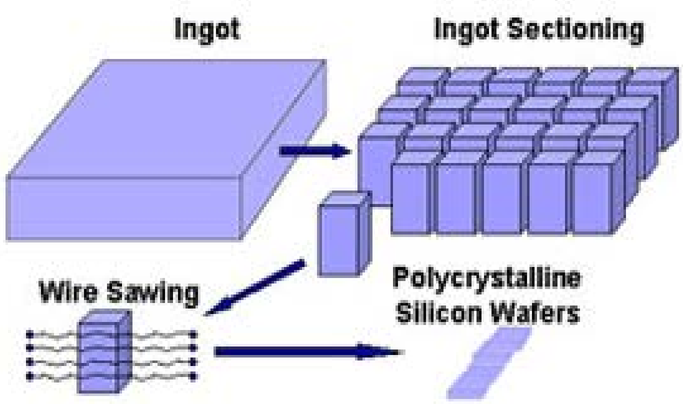


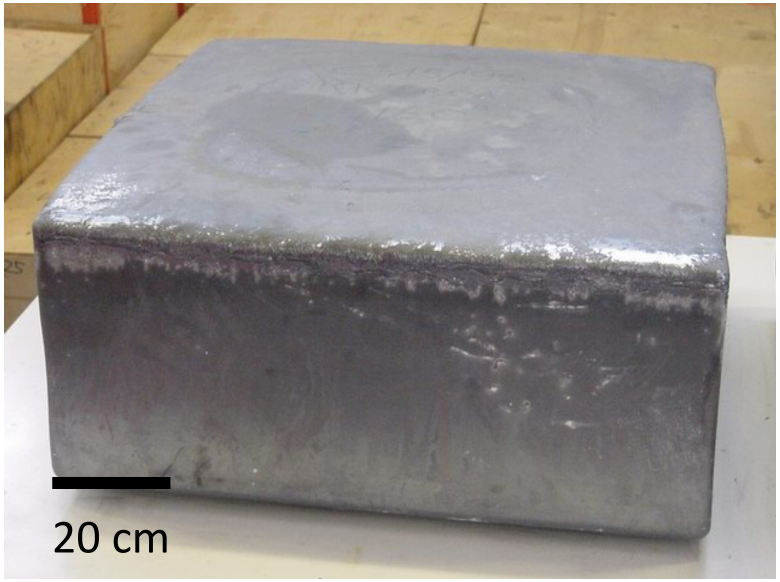
mc-Si directional solidification

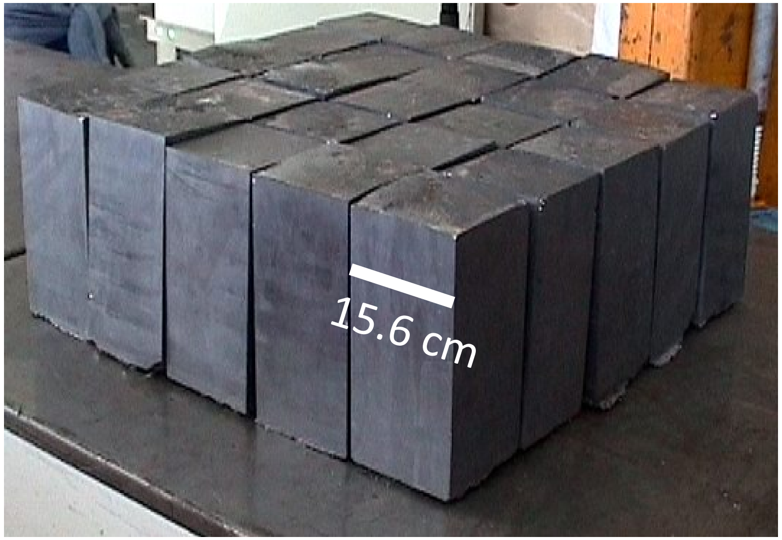




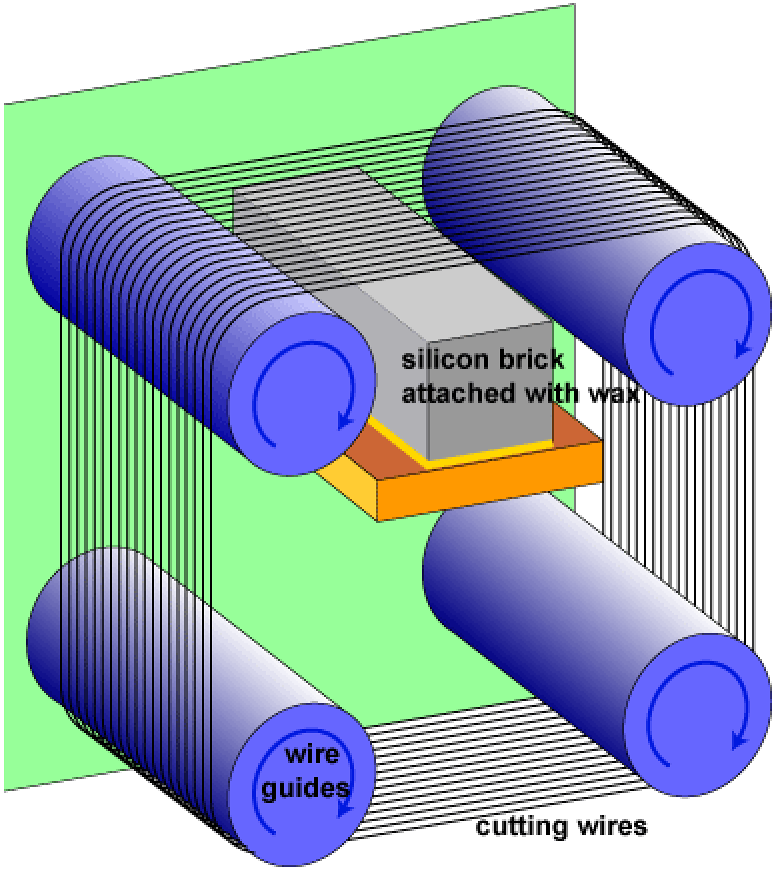
Wafering

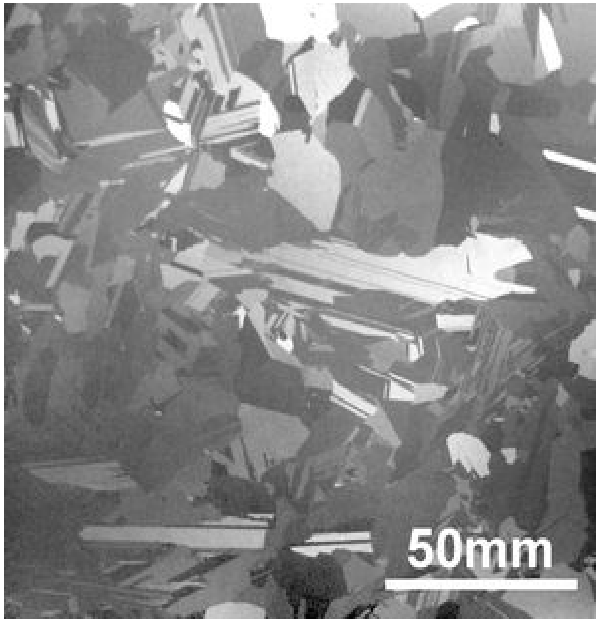

Ingot
Ingot Sectioning
Wire Sawing
Polycrystalline
Silicon Wafers


20 cm

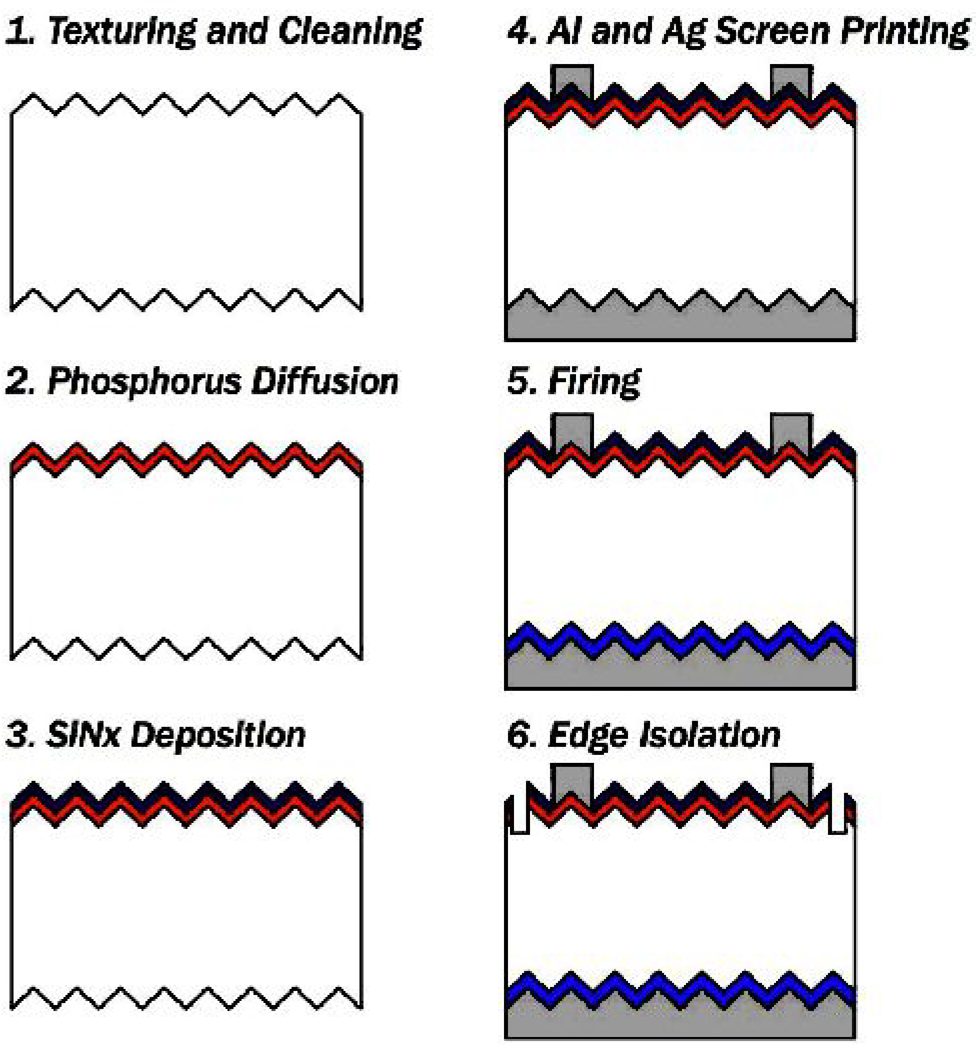

15.6 cm

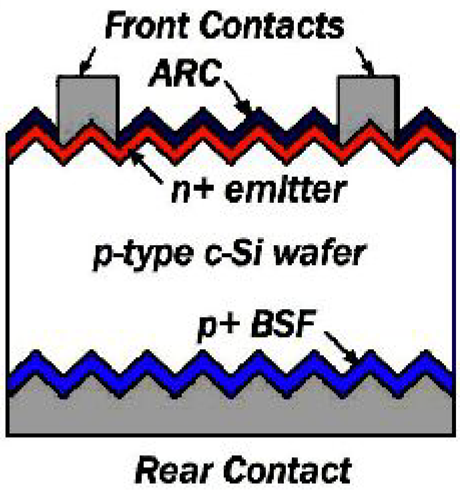
Wafering

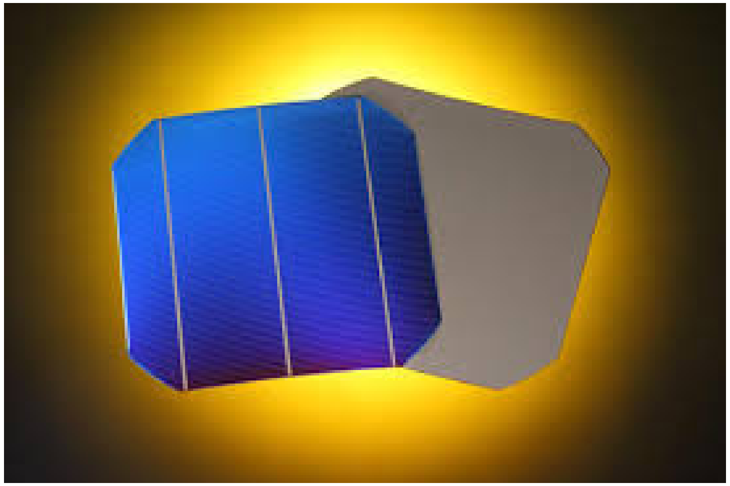

silicon brick
attached with wax
wire
guides
cutting wires


50mm

Screen Printed Solar Cells

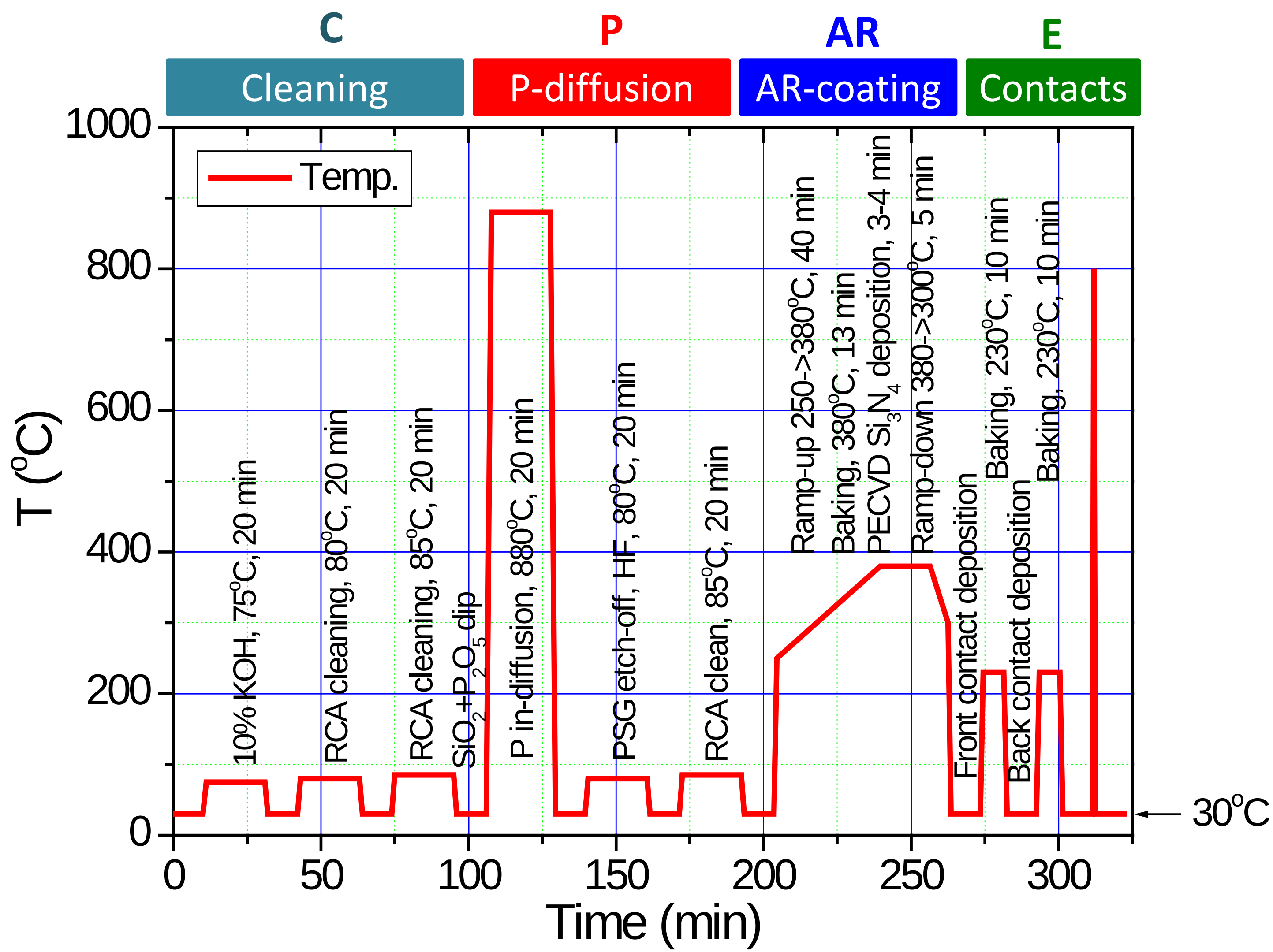






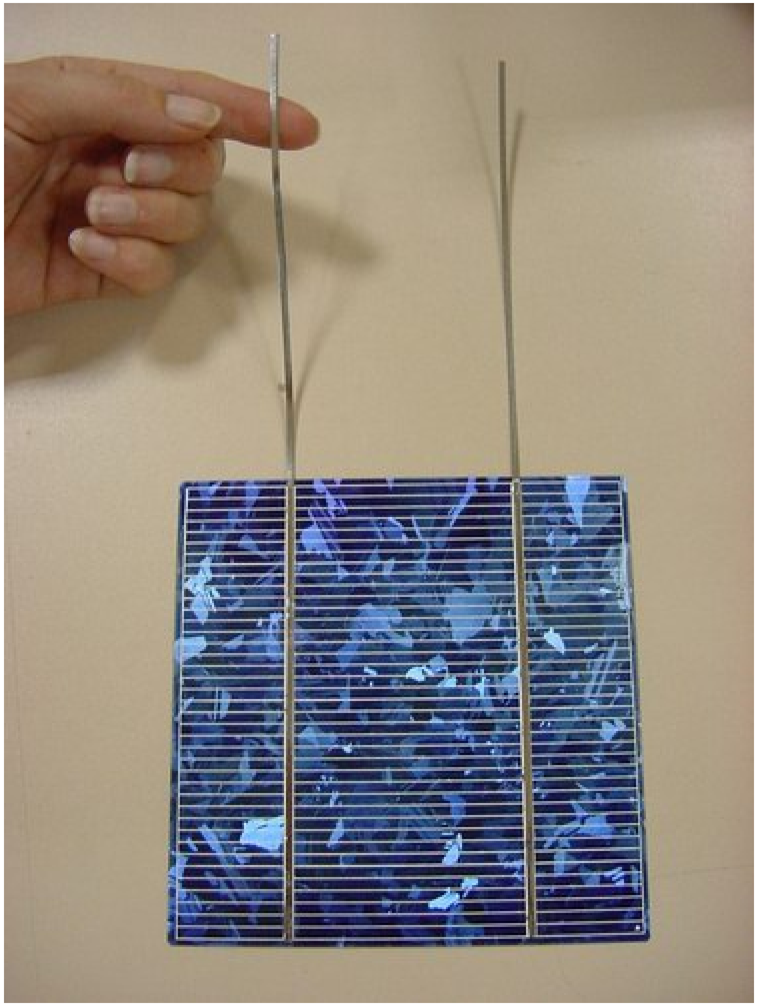
http://www.intechopen.com/

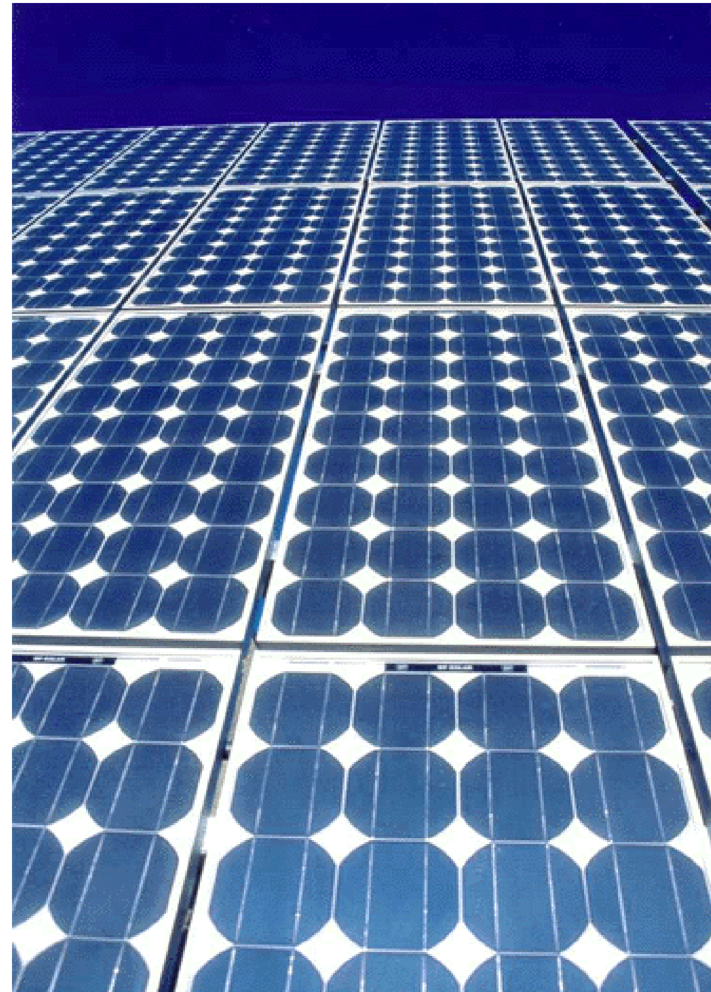
Solar cell fabrication process



[K. Lauer et.al, Energy Proc. 38, 589 (2013)]

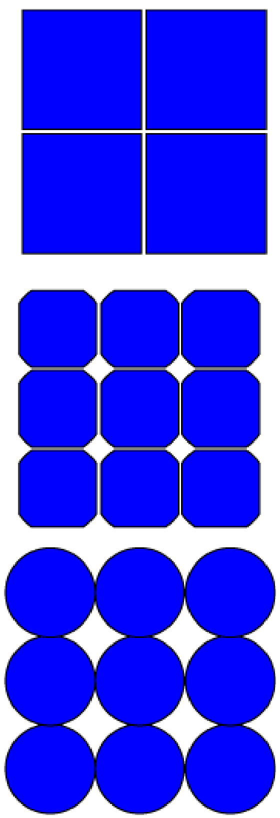
From cells to modules

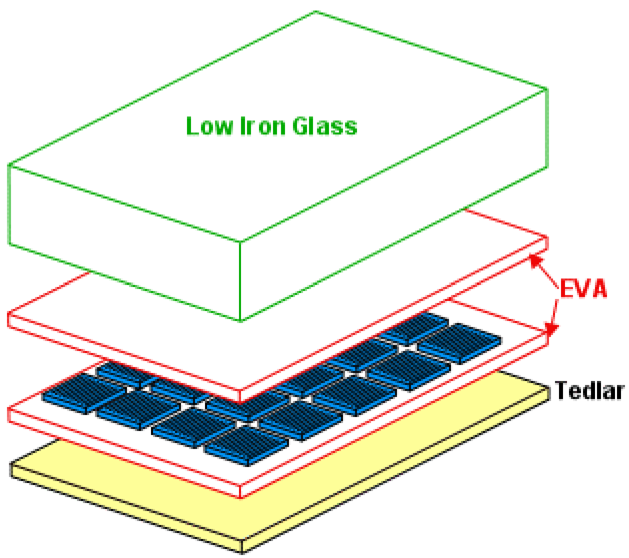




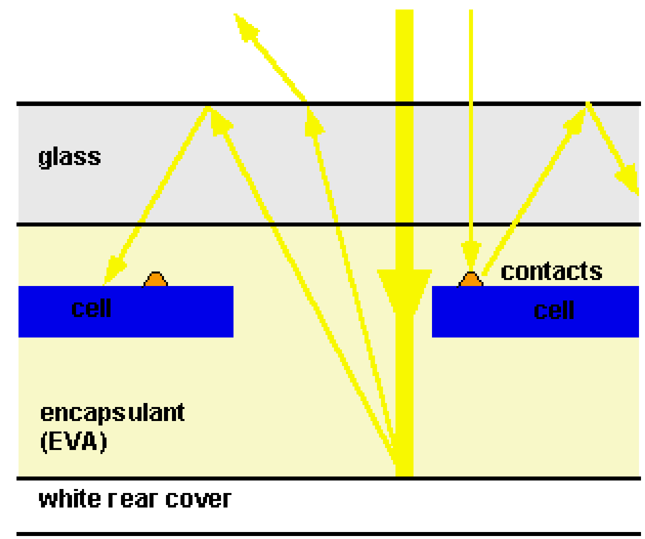
Module structure

A PV module consists of a number of interconnected closely packed solar cells encapsulated into a single, long-lasting, stable unit. Module lifetimes and warranties on bulk silicon PV modules are over 20 years. A typical warranty will guarantee that the module produces 90% of its rated output for the first 10 years and 80% of its rated output up to 25 years.

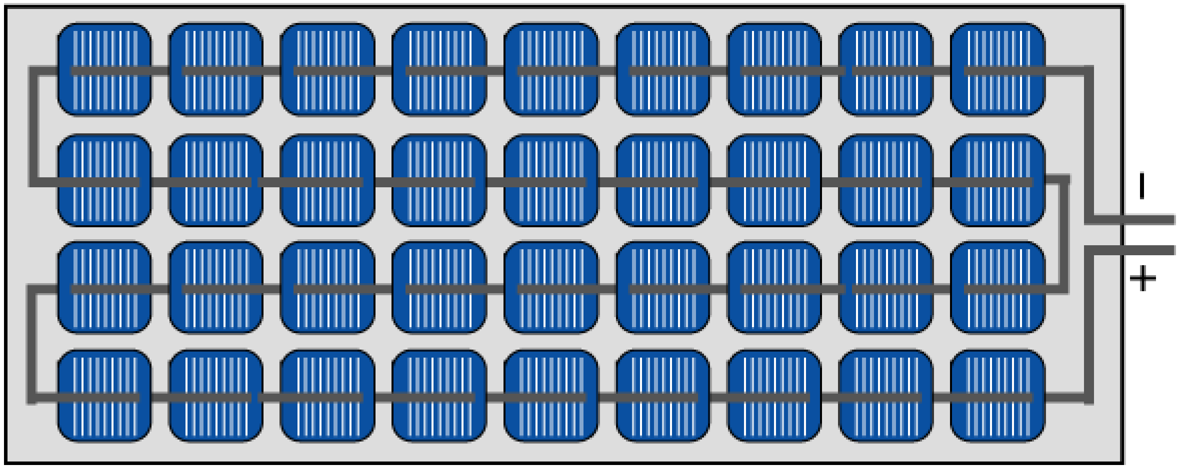




*)EVA - ethyl vinyl acetate



Module circuit design

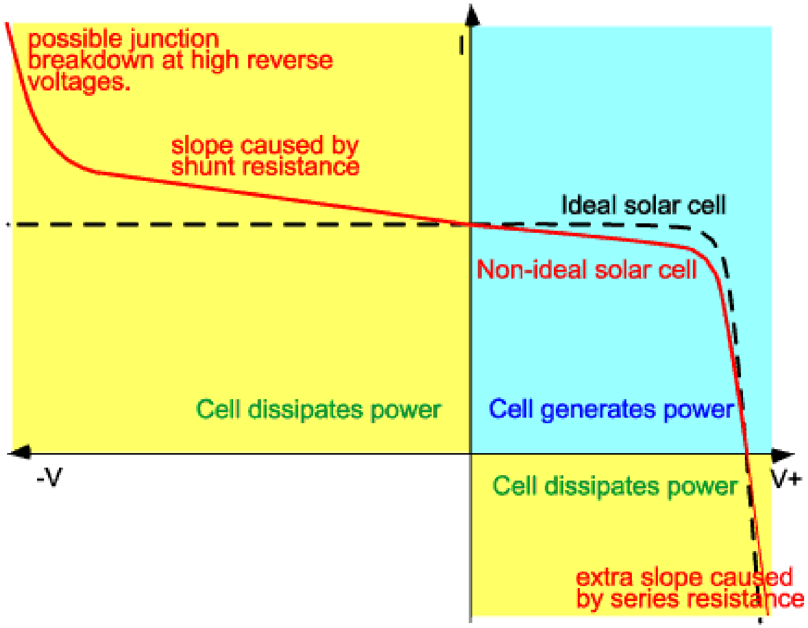


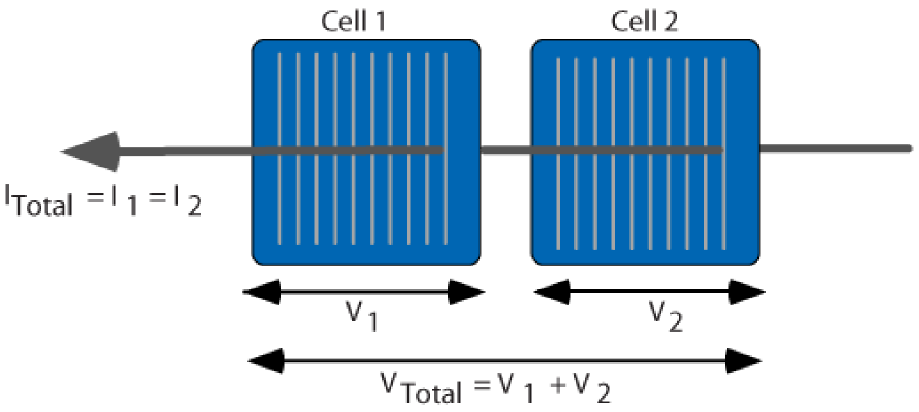
An individual silicon solar cell has a voltage of just under 0.6V under 25 °C and AM1.5 illumination: 0.6×36=21.6 V.

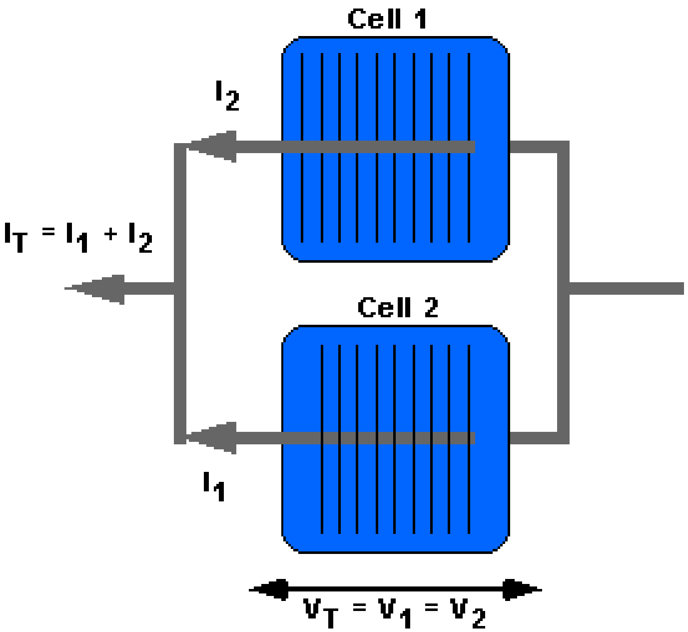
$$I_T = M \cdot I_L - M \cdot I_0 \left[\exp\left(\frac{q \frac{V_T}{N}}{nkT} \right) - 1 \right]$$

where: N is the number of cells in series; M is the number of cells in parallel; I_T is the total current from the circuit; V_T is the total voltage from the circuit; I_0 is the saturation current from a single solar cell; I_L is the short-circuit current from a single solar cell; n is the ideality factor of a single solar cell; and q, k, and T are constants.

Mismatch effects

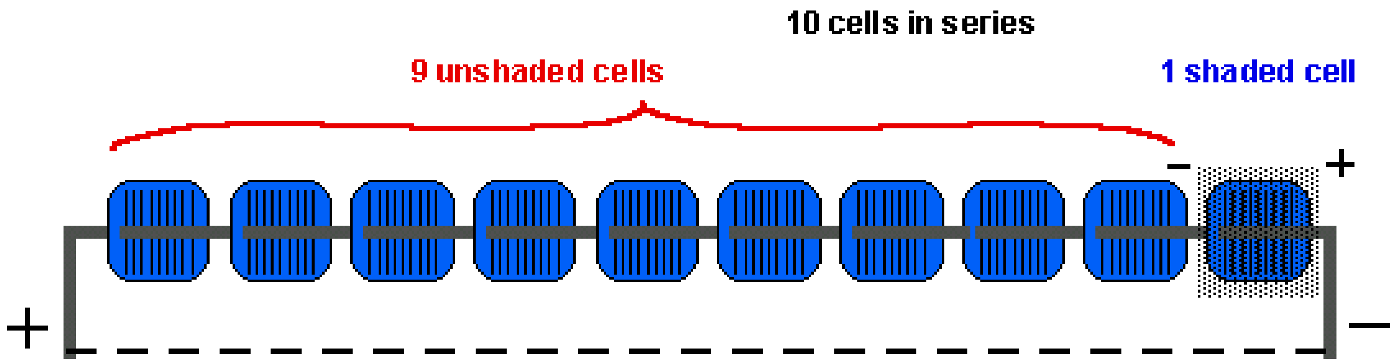




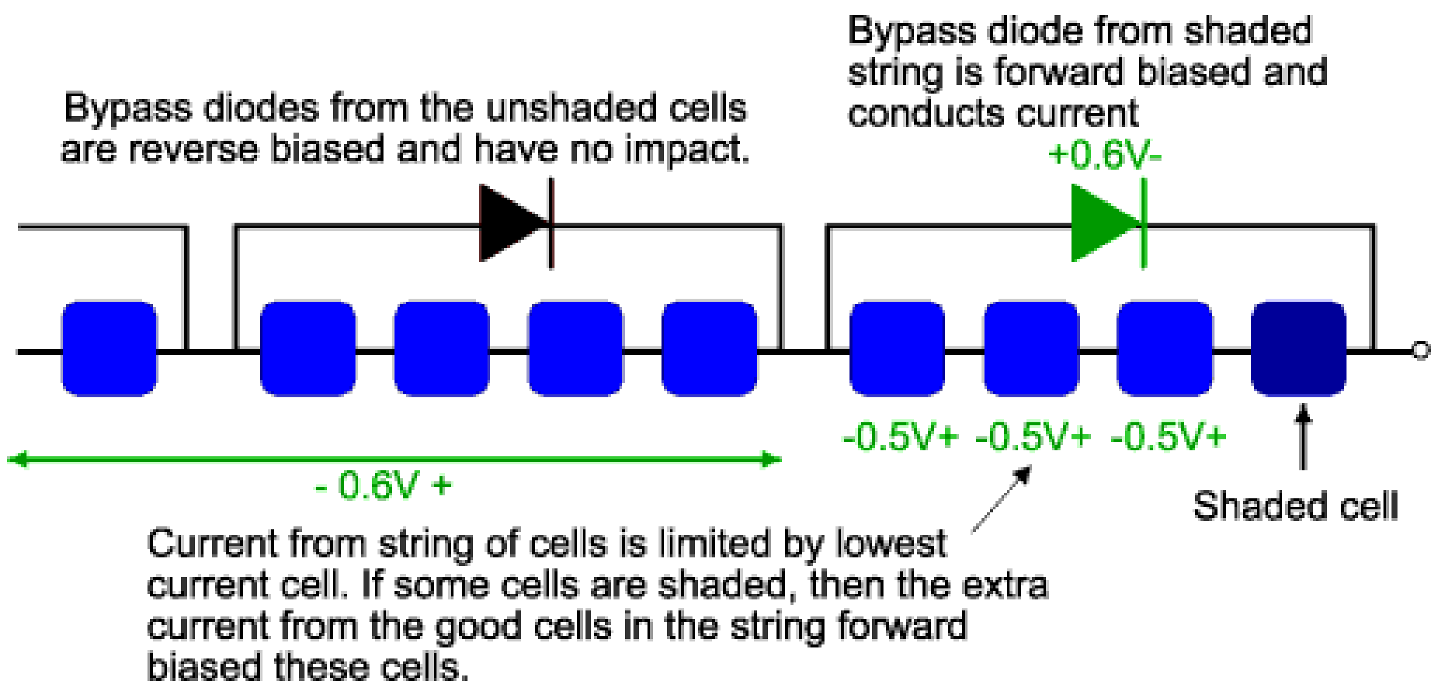


http://www.pveducation.org/

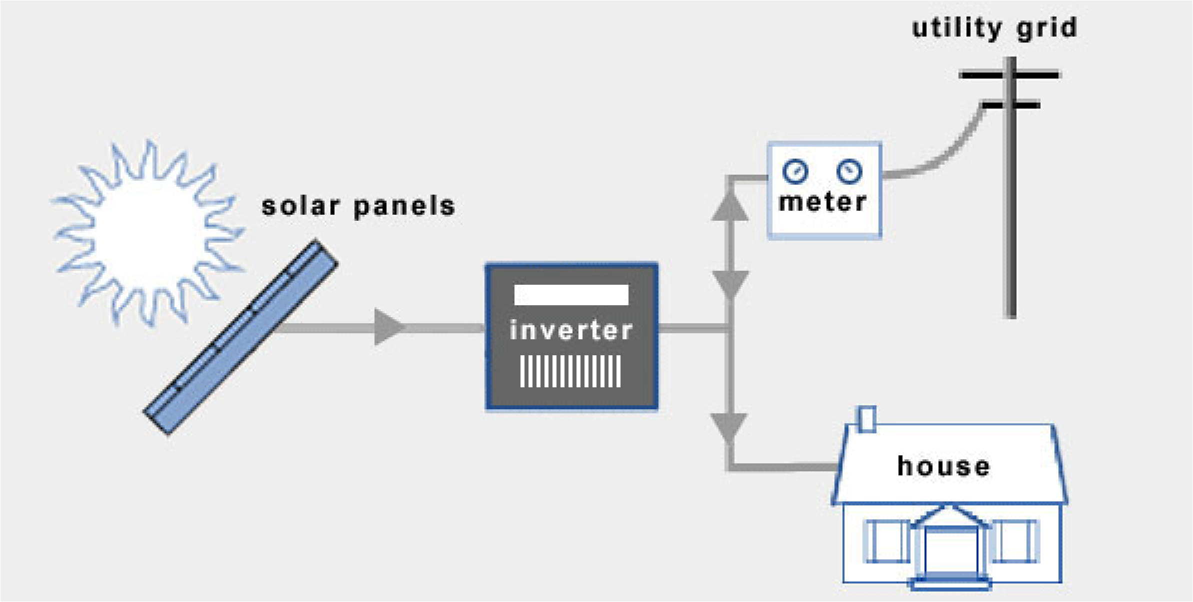
Shading effects and bypass diodes



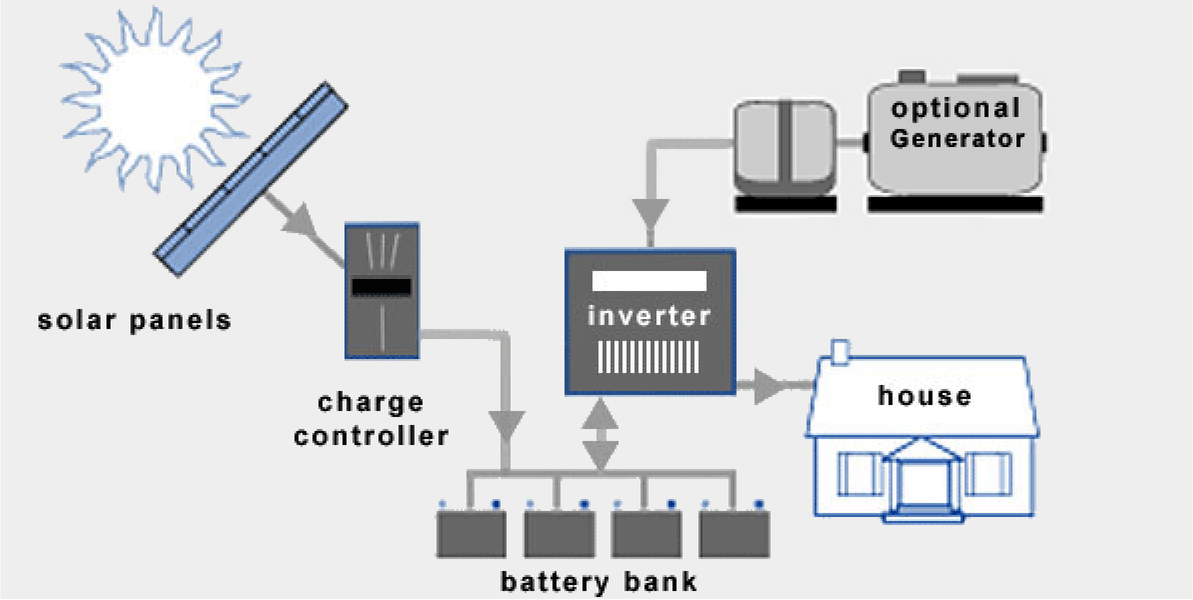
If the terminals of the module are connected in series (I_{SC}), the power from the unshaded cells is dissipated across the shaded cell.



On-grid vs. off-grid alternative



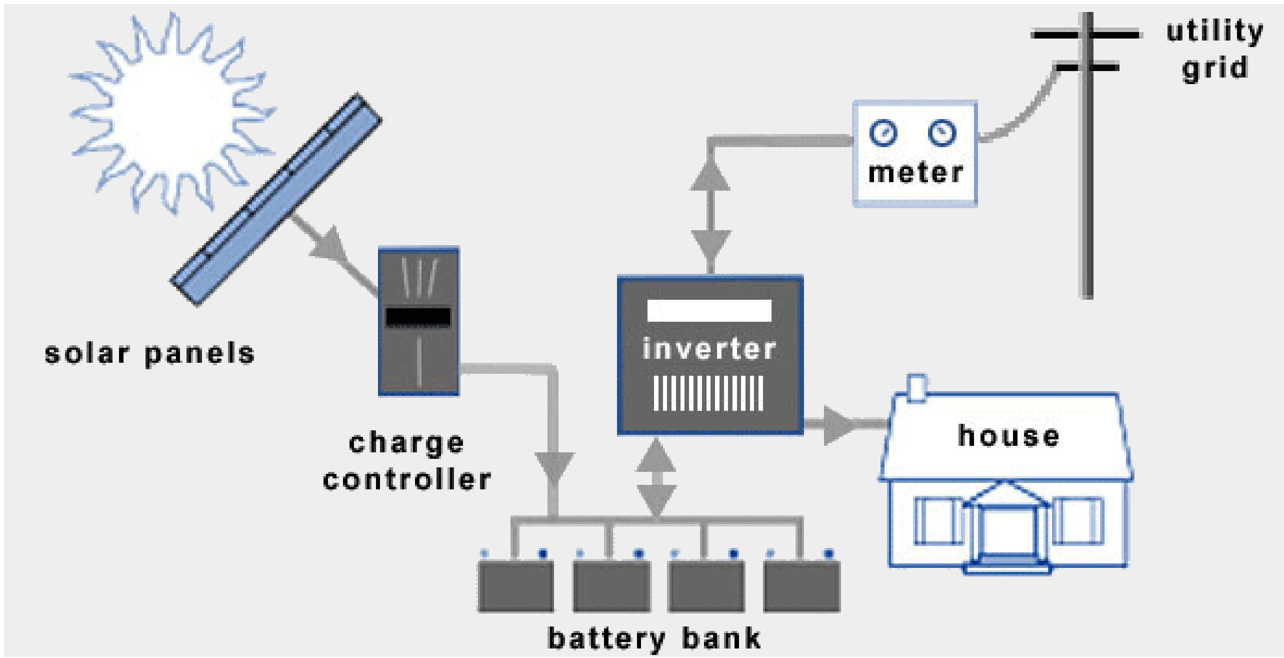
On-grid



Off-grid

http://energyinformative.org/

Hybrid solar system

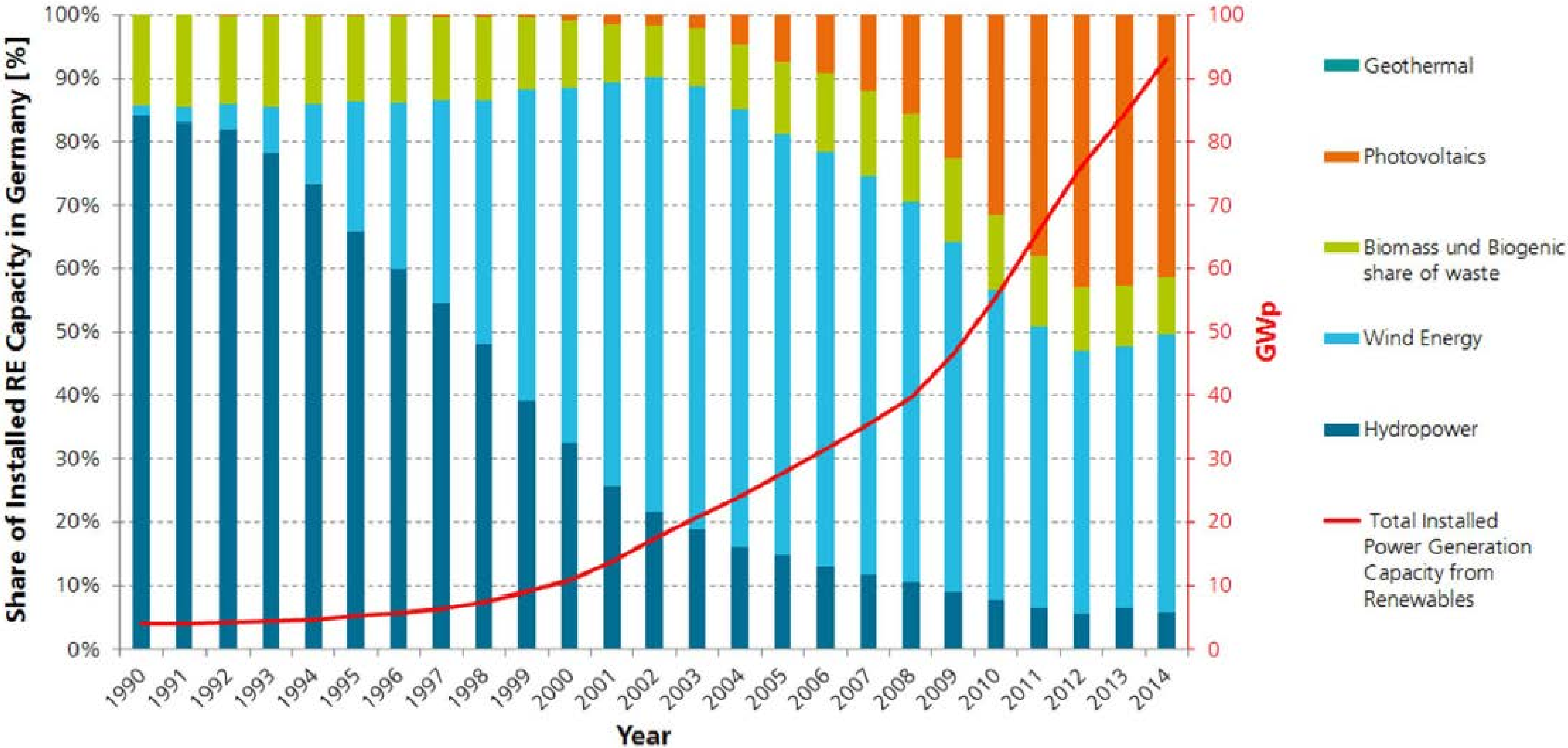


TESLA

Each Powerwall has a 7 kWh energy storage capacity, sufficient to power most homes during the evening using electricity generated by solar panels during the day.

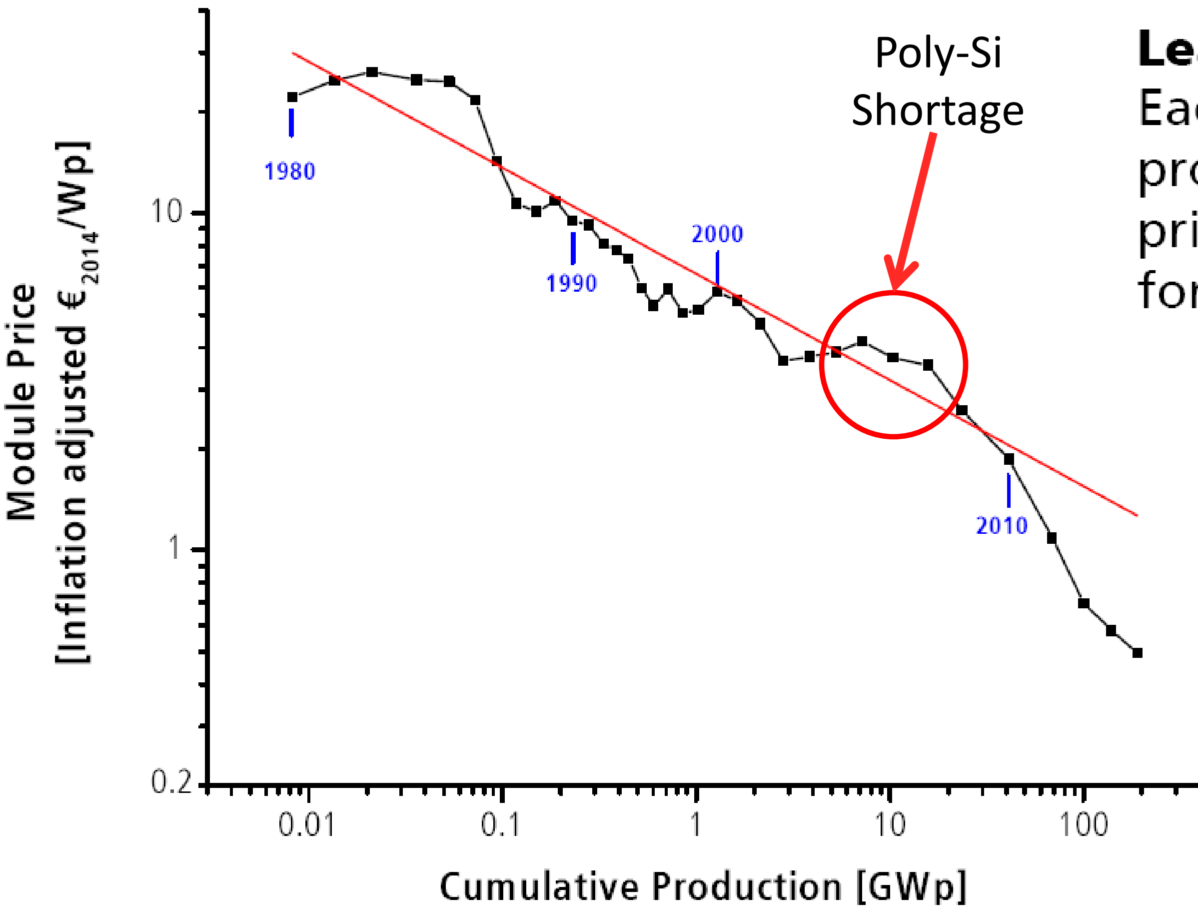
https://www.teslamotors.com

Electrical capacity of renewable energy sources for Germany



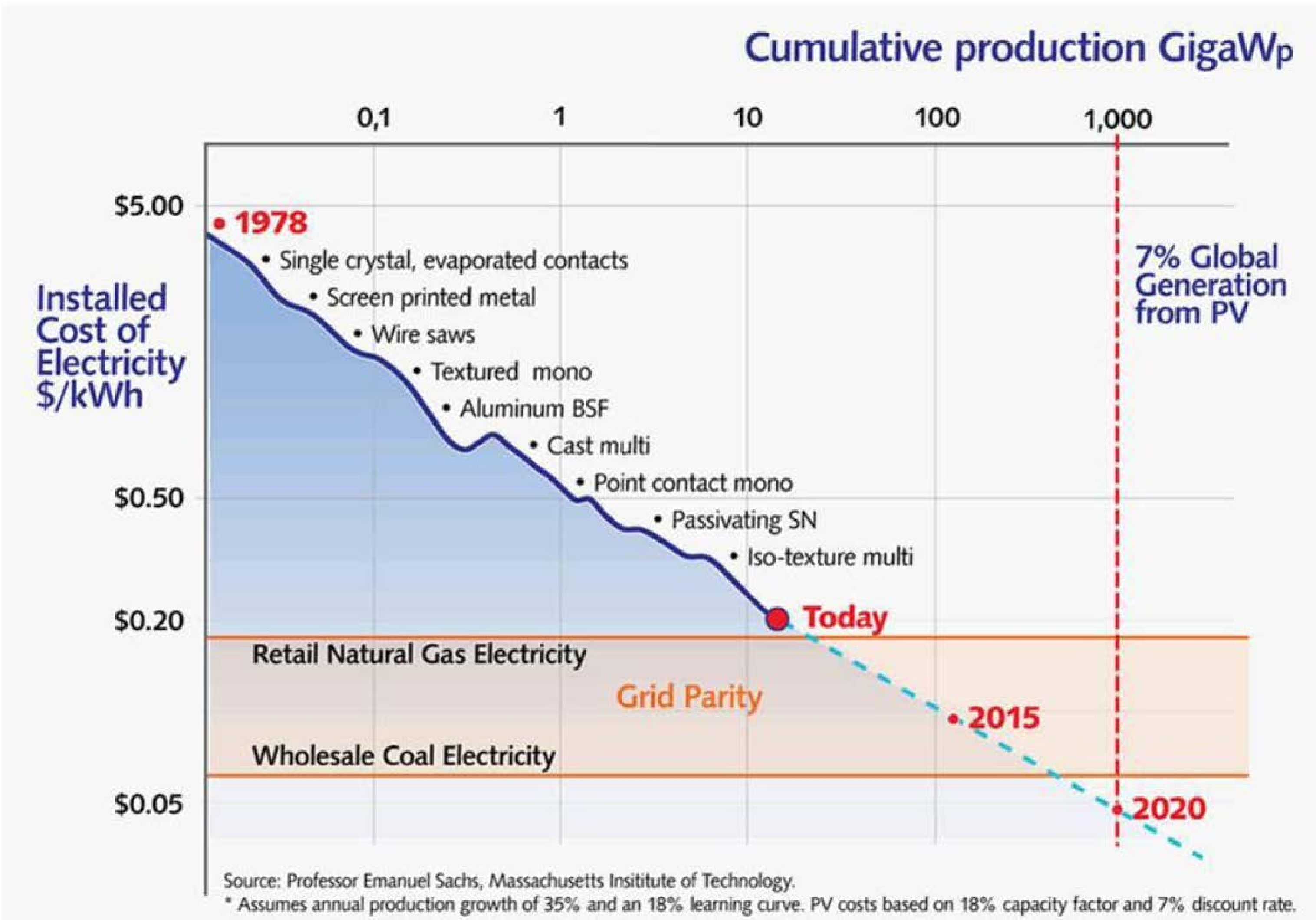
In 2014 about 28% of the electricity in Germany was generated by renewable energy (RE) sources according to BMWi.

Price Learning Curve



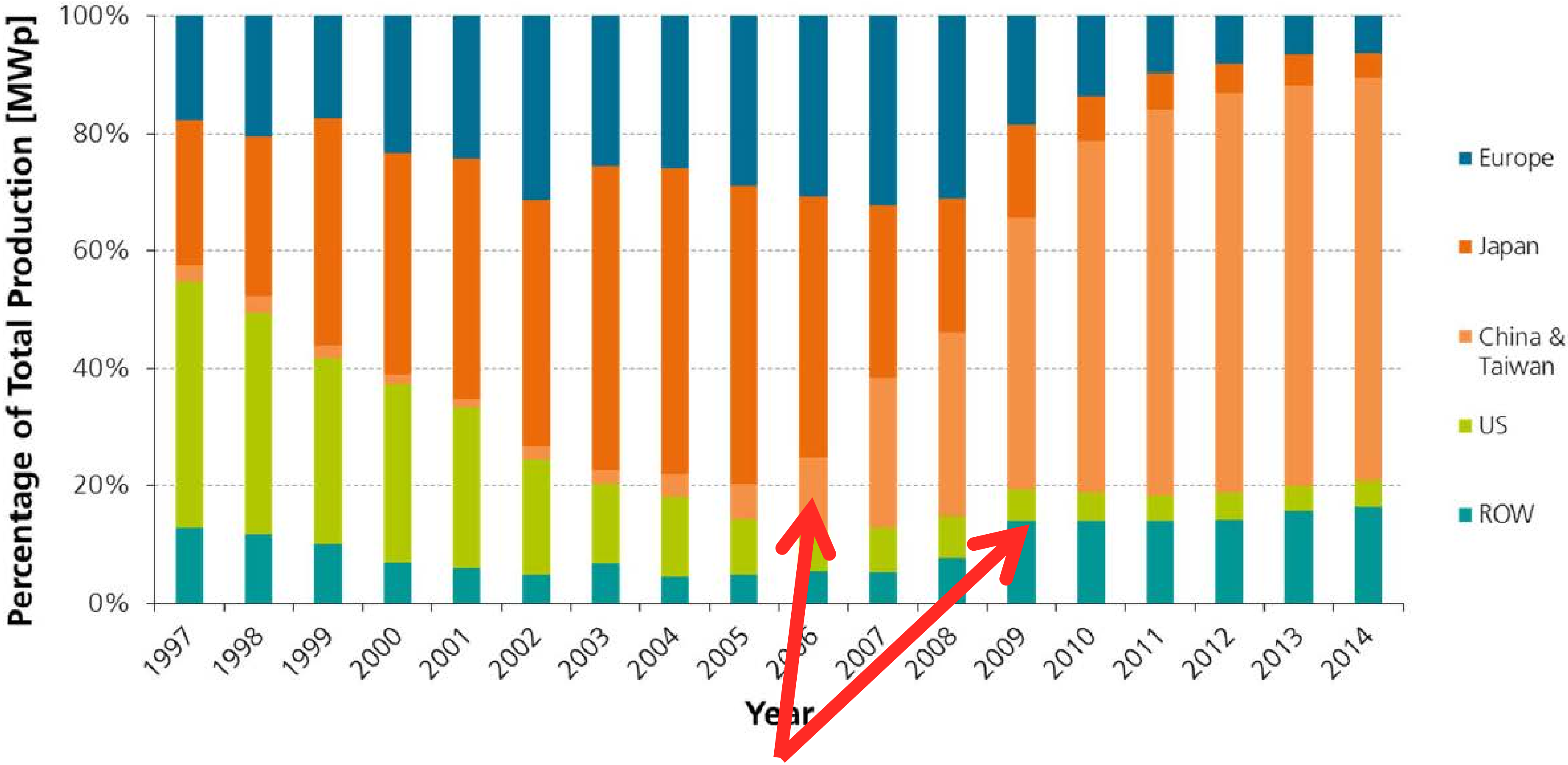
Learning Rate:
Each time the cumulative production doubled, the price went down by 19.6% for the last 34 years.

Innovations pushing the price down



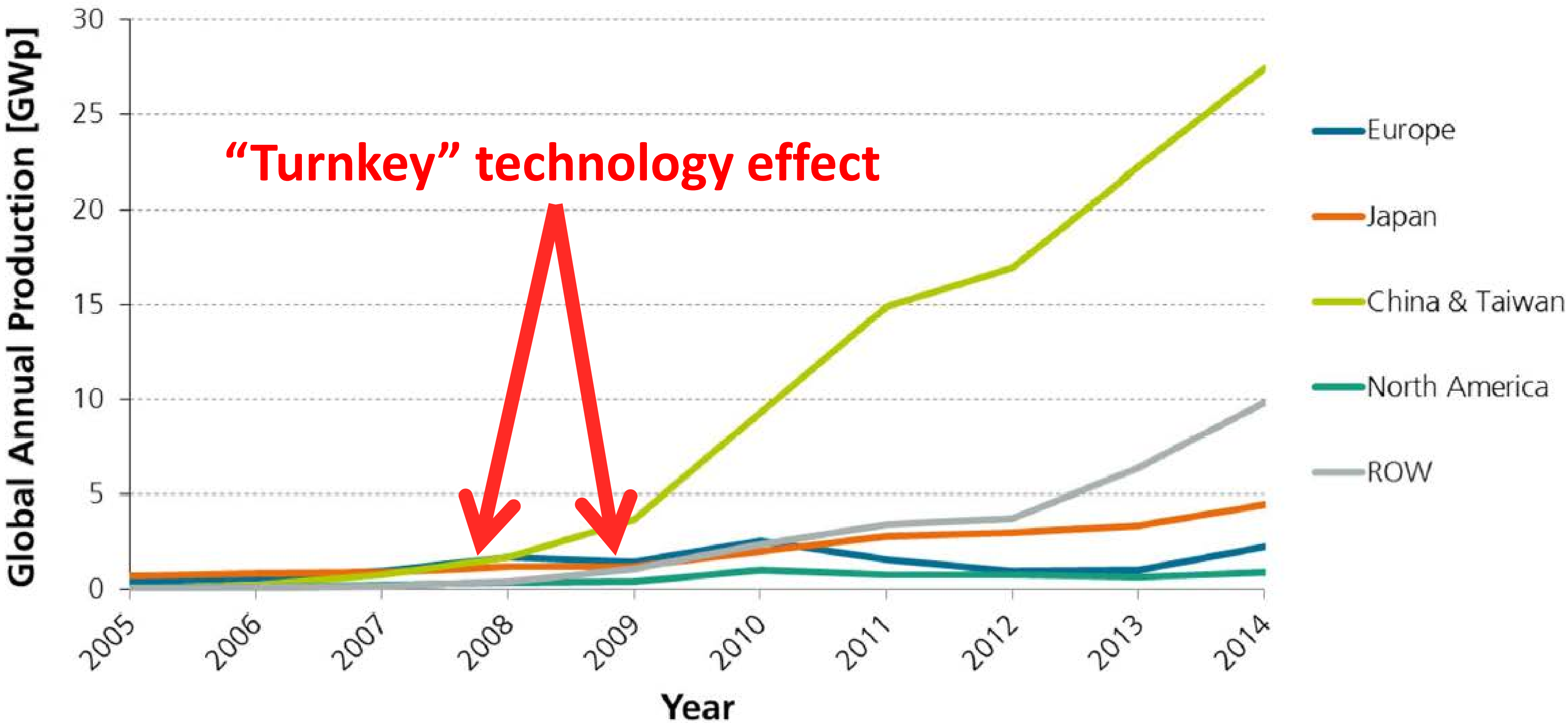
http://paxonbothhouses.blogspot.de/2014/04/has-grid-parity-arrived.html
http://www.treehugger.com/natural-sciences/15-photovoltaics-solar-power-innovations-you-must-see.html

PV Module Production by Region 1997-2014

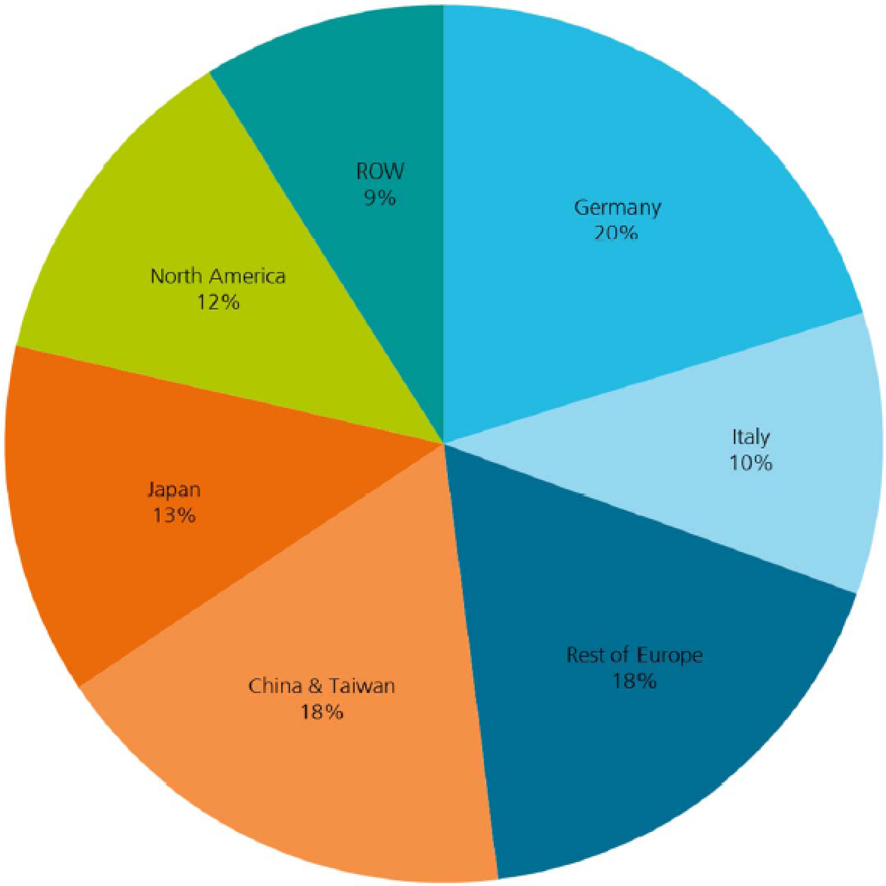


"Turnkey" technology effect

PV Industry Production by Region



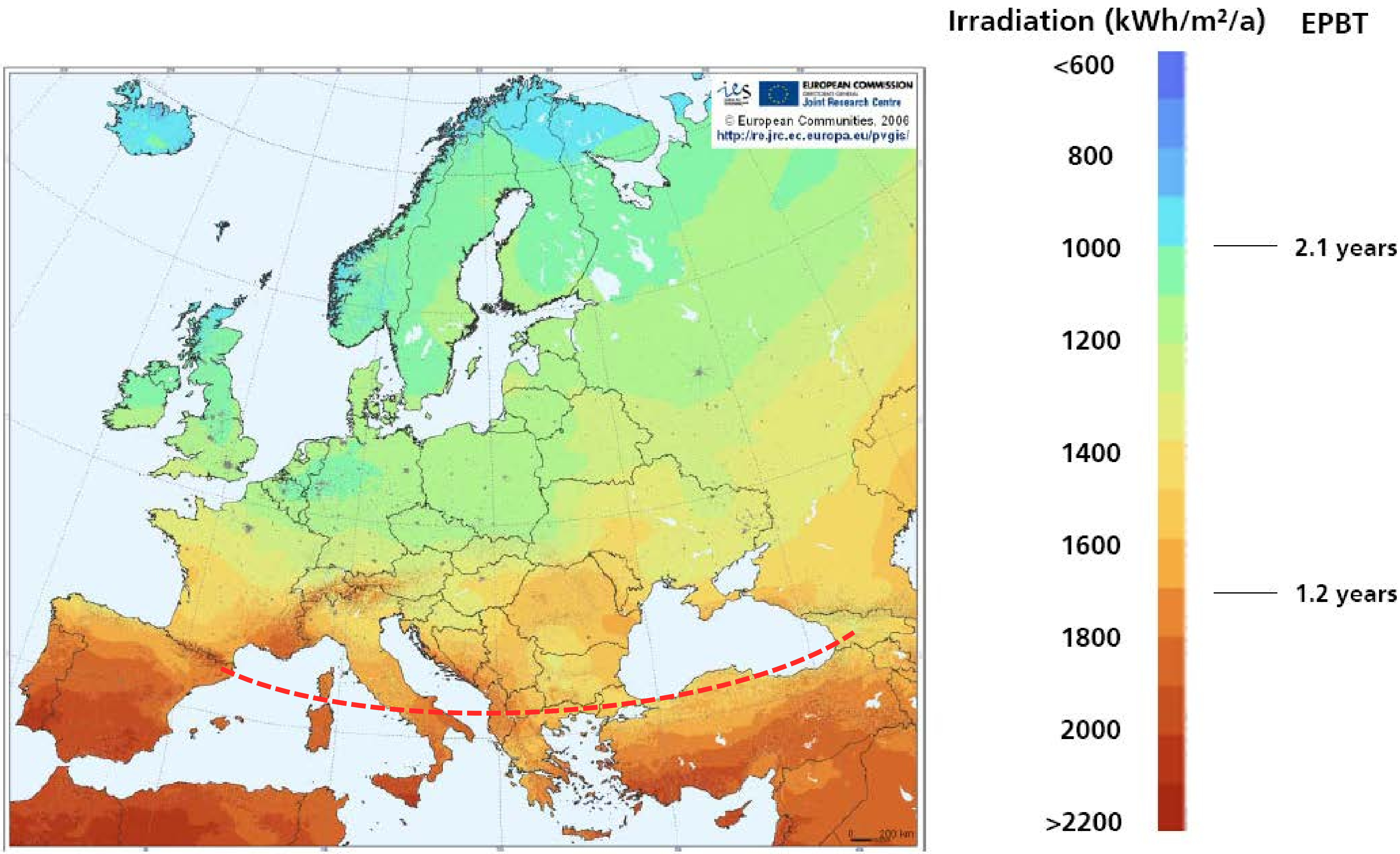
Global Cumulative PV Installation by Region
Status 2014



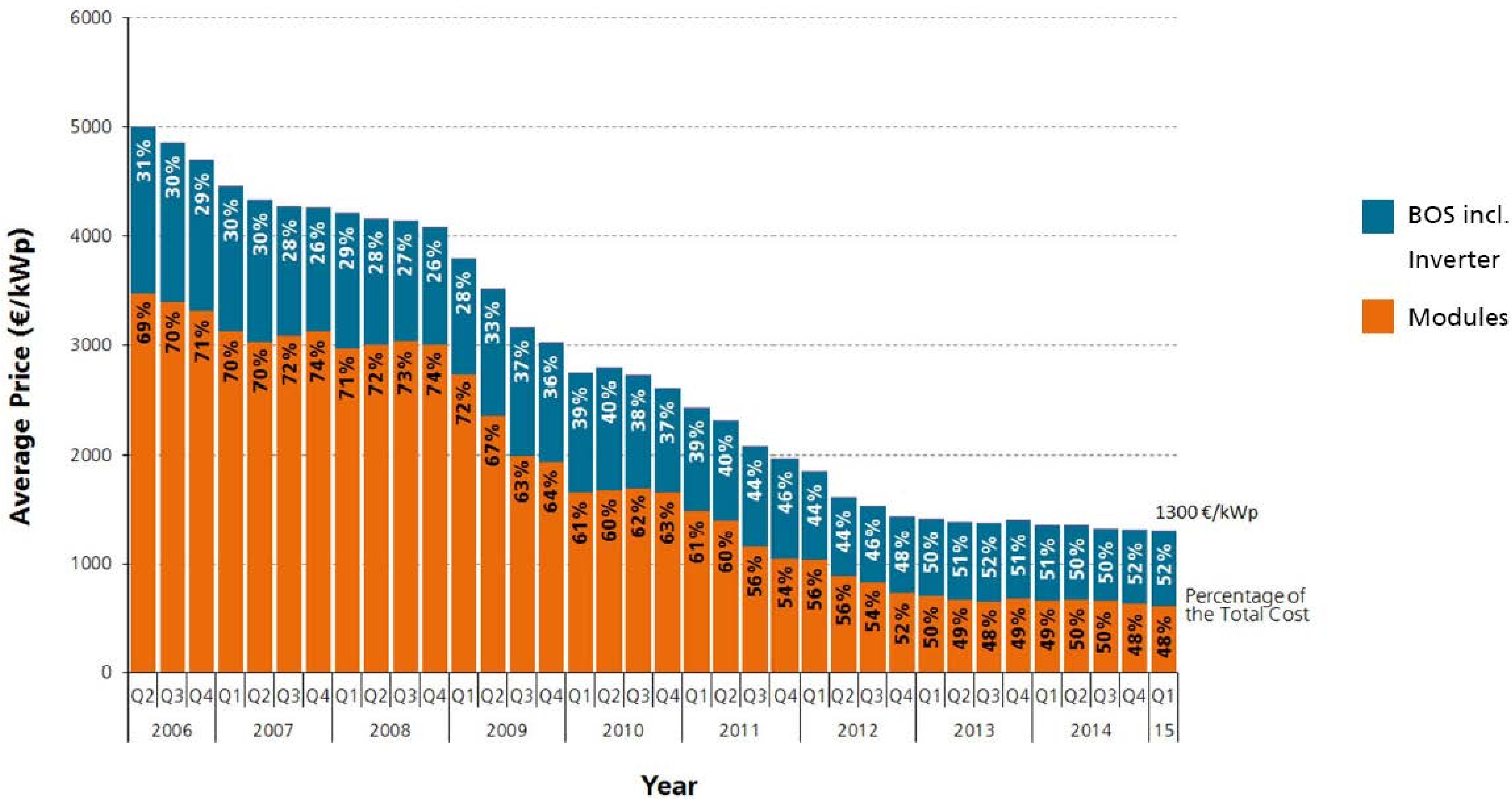
The total cumulative installations amounted to 183 GWp at the end 2014.

All percentages are related to total global installations, including off-grid systems.

Energy pay-back time of mc-Si PV rooftop systems - geographical comparison



Average Price for PV Rooftop Systems in Germany (10kWp - 100kWp)



ფოტოვოლტაიკის ეკონომიკა და ფოლისოფია.

დასკვნები და მომავლის პერსპექტივა.

http://www.siemens.com/